Acknowledgements

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During the supplemental data collection phase of the project, groundwater samples were provided by many of the local environmental consulting firms. For our own groundwater sample collection, we would like to thank Conoco-Phillips (formerly TOSCO - Circle K), the ADEQ State Lead Unit, and Tierra Dynamic, Inc. for providing access to their sites, or to sites that they manage. Thanks also to our subcontractors, as they provided the support necessary to accomplish our field characterization work: ATC Associates, for their logistical support and assistance with the field studies; Yellow Jacket Drilling, for their drilling expertise and support of the project; ProSonic Corporation, for their GeoProbe expertise in the Arizona environment; and Southwest Geomatics, for their contributions to our surveying study. We would also like to acknowledge Martin Minter, for his voluntary contribution of time during the GIS spatial analysis portion of this study, and Cristin Bruce, for her assistance in groundwater sample analysis during site characterization studies.

Finally, we wish to thank our Arizona Groundwater Study Project External Technical Peer Review Panel for their valuable advice and insightful comments throughout all phases of this project. The panel members included Dr. Herman Bouwer (formerly of the U.S. Department of Agriculture Soil Water Conservation Lab), Dr. David Huntley (California State University, San Diego), and Dr. William Rixey (University of Houston).

EXECUTIVE SUMMARY

Arizona has had over 9,000 underground storage tank (UST) facilities on file at the Arizona Department of Environmental Quality (ADEQ). Of these, about 4,300 have attained leaking underground storage tank (LUST) status. This study was commissioned by the Arizona State Legislature to study LUST impacts to groundwater resources in Arizona. It was felt that a comprehensive state-wide look at the nature of LUST impacts to groundwater would help guide future cost-effective and protective management of LUST sites. This study was directed by the Underground Storage Tank Policy Commission, the contracting was administered by ADEQ, and the study was conducted by Arizona State University (ASU) in full cooperation with ADEQ, the UST Policy Commission, UST site owners and operators, and environmental consulting firms that deal with LUST site issues.

This study involved the review of 417 ADEQ LUST site files and compilation of relevant data from 323 of these sites into an electronic database. It also involved the collection and analysis of over 700 supplemental groundwater samples, the assessment of aquifer flow properties from 32 wells at 11 sites, and more detailed characterization at six LUST sites representative of a range of conditions at AZ LUST facilities. In addition, over 300 groundwater level measurements were performed and 175 monitoring wells were re-surveyed in order to assess errors in standard practice and their impact on groundwater flow direction determination. An empirical analysis of groundwater impacts at AZ LUST sites was conducted using these data sets, with emphasis on identifying relationships between site conditions (e.g., geology, depth-to-groundwater, etc.) and groundwater impacts. Finally, a combined theoretical-spatial (GIS) analysis was performed to identify LUST scenarios posing the greatest threats to use of groundwater resources.

The main body of this report and the appendices describe the methods used, the data collected, and observations from the empirical data analysis.

With respect to the selection of LUST site files for this study, readers should note that:

- LUST site files were not selected randomly for review - they were selected to ensure representation of a range of hydrogeologic settings as well as a wide geographic representation across the State of Arizona. Files known to contain MTBE concentrations in groundwater were targeted. For the analysis of remediation performance, "closed" LUST site file reviews were emphasized.

- The LUST site files reviewed were associated with releases reported in the 1978 - 2001 period, with the majority (97%) of files corresponding to releases reported prior to implementation of the 1998 UST upgrade requirements.

Therefore, readers should be careful not to draw overly-broad conclusions from the observations presented in this report. For example, because the results of this study are based predominantly on data from LUST sites having older (pre-1998 upgrade) UST installations, one might argue that the results are not directly applicable to newer (post-1998) tank installations and newer fuel formulations.

To place the results of this study in proper context, it is important to understand typical LUST site settings and release scenarios; for example:

- The majority of the selected LUST sites (84%) were located in areas where industrial/commercial and residential areas could be found within 1/4 mile of the site; the available information suggested that, on average, three other UST sites were located within 1/4-mile distance.

- The majority of the selected LUST sites were impacted by gasoline releases; the volumes of product released and the timing of the releases were generally unknown; all major components (tanks, lines, dispensers) of those UST systems (primarily pre-1998 systems) appeared to have been susceptible to failure.

These typical LUST site settings place practical restrictions on accessible soil sampling and groundwater monitoring well locations. The close proximity to other UST/LUST sites complicates data interpretation. Unknown release dates, locations, and volumes lead to a greater emphasis on the use of soil and groundwater sample analysis in the decision-making process.

The hydrogeological characteristics of LUST sites reviewed for this study can be summarized as follows:

- The subsurface at most sites was composed of unconsolidated sediments, and the most prevalent qualitative geologic descriptors were "interbedded sands/silts/clays", "mixed sands/silts/clays", and "mixed sands/gravels/cinders".

- Quantitative subsurface characterization data (e.g., hydraulic conductivity) were available in very few site files.

- The depth-to-groundwater was less than 50 ft at 50% of the sites with depth-to-water data, and was greater than 100 ft at only about 10% of the sites.

- For sites with enough data to confidently determine dominant flow directions and horizontal hydraulic gradients (approximately 190), the gradients ranged from 0.0005 to 0.40 ft/ft; approximately 50% of the sites had gradients less than 0.006 ft/ft and 15% of sites had gradients greater than 0.02 ft/ft.

- For sites with sufficient data to determine apparent historical variations in flow direction (approximately 190), 75% had variations in flow direction in excess of 20 degrees, and 40% of sites had variations in excess of 45 degrees (see related discussion below of groundwater elevation determination errors).

The absence of quantitative aquifer characterization data precludes one from making confident estimates of groundwater velocity - a quantity of interest for many risk-based decision-making processes. The lack of quantitative information also necessitates reliance on the subjective qualitative descriptions of site hydrogeology, but there was little variation in the qualitative descriptions of the sites reviewed for this study. The apparent historical variations in flow directions suggest that non-traditional site assessment paradigms and conceptual models are needed for collecting and interpreting site assessment data. For example, the most commonly used LUST site conceptual model is the simplistic one in which groundwater flows horizontally in one direction, with dissolved contaminants also migrating only in that direction. Site investigation strategies will be based on this conceptual model (e.g., installing wells in a line along the assumed flow direction) and data will be interpreted in the context of this conceptual model. If the actual groundwater flow and contaminant migration are not adequately represented in the conceptual model, then this leads to poor characterization and erroneous conclusions.

A significant feature of this study relative to other state-specific LUST impact studies is the characterization of typical LUST site assessment data. Understanding the characteristics of the LUST site assessment data is critical to proper data interpretation and data use in decision-making. Of particular significance are the following observations from the LUST site file review:

- The majority of LUST site data were generated from conventional soil boring and groundwater monitoring well sampling activities.

- 10 or more soil borings were conducted at about 60% of the sites and, on average, four samples per boring were sent for laboratory analysis.

- 50% of sites had 6 or more groundwater monitoring wells installed; the majority of wells were constructed with 10 - 45 ft long screened intervals; the spatial distribution of wells favored the source zone and cross-gradient areas. In this report, the LUST site "source zone" is the subsurface region where one finds petroleum liquid (e.g., gasoline) in the soil pores.

- For the 270 sites having groundwater monitoring wells, only about 70% had sufficient hydraulic data to confidently determine a dominant flow direction.

- For the sites with sufficient hydraulic data to confidently determine dominant flow directions (approximately 190), down-gradient monitoring wells were not present at about 30% of sites, and 60% of the sites had only one or two down-gradient monitoring wells. Only 16% of all wells (1 of 6) at these sites were classified as being hydraulically down-gradient of the source zone. About 70% of the down-gradient wells were located within 250 ft of the UST system, and about 90% were located within 500 ft.

- Typical measurement errors associated with groundwater elevation determination can be large enough to significantly affect the determination of groundwater flow direction at many AZ LUST sites; in particular, data sets created with successive partial well surveys have the greatest potential to introduce errors; use of different groundwater level sensors in the same sampling event can also introduce significant errors.

- Quantitative aquifer characterization data (i.e., hydraulic conductivity) were available for only about 10% of the sites having groundwater quality investigations, and the data indicated no clear correlation between qualitative geologic descriptions (i.e., “sands”, etc.) and measured quantitative properties.

- Limited chemical concentrations in groundwater data were available for historically non-regulated fuel additives like MTBE, TBA, and the alcohols (more data were available for MTBE concentrations in groundwater than for the alcohols).

Of significance here are the implications that these observations have with respect to the adequacy of assessment of dissolved plume impacts at LUST sites. For example, the selection of proper sampling locations, the determination of the extent of dissolved contamination, and the use of these types of data for risk-based decision-making are difficult when the flow direction is uncertain, the groundwater velocity is unknown, and the extent of the more soluble fuel components is unknown.

Based on the data available for this study, the following were concluded about impacts at gasoline-release sites:

- Source zone sizes typically ranged in size from 1,000 to 10,000 ft^2 (50% of sites). Only 14% of sites had source zones smaller than 1,000 ft^2 and 4% of sites had source zones larger than 100,000 ft^2.

- Free-product (liquid gasoline) was observed in one or more wells at about 50% of the sites with groundwater quality data; free-product thicknesses measured in wells ranged up to 12.6 ft, but were typically less than 2 feet.

- Frequently detected chemicals-of-interest for this study included benzene, toluene, ethylbenzene, xylenes, trimethylbenzenes, naphthalene, MTBE, and TBA – these were typically found in the 100 to 10,000 ug/L range in source zone groundwater samples.

- MTBE data was only available for two-thirds of the sites with groundwater quality data. MTBE was not detected at all sites, but its occurrence was relatively widespread across the state, including rural areas.

- The alcohols (other than TBA) and fuel additives DIPE and ETBE were detected very infrequently in source zone groundwater.

- Given the spatial distribution of monitoring points (i.e., two or fewer down-gradient wells at many sites, and limited data from down-gradient distances in excess of 400 ft as discussed above), it is difficult to draw defensible global conclusions regarding the extent of down-gradient chemical migration. The collective data from the file review process indicated that concentrations in groundwater as high as 1,000 ug/L extended as far as about 500 ft away from some UST systems, but the data also suggested that concentrations in groundwater in excess of 100 ug/L were rarely detected at distances greater than this (although it is important to note that there were very few wells at greater distances too). The collective data also suggested that the spatial extent of MTBE and benzene dissolved plumes were similar.

- The additional site assessment data collected at six sites contradicts the last statement in the paragraph above; this data showed dissolved MTBE plumes that attenuated with distance more slowly than the associated dissolved benzene plumes.

- Based on a visual review of the data, there was no discernible increasing or decreasing trend in benzene or MTBE concentrations in groundwater at most sites.

Of particular interest here is the discrepancy between the observations from the comprehensive analysis of the file review database and the results from the focused supplemental characterization at six LUST sites. This raises questions about the validity of conclusions drawn from large database analyses (especially as they are related to the spatial extent of groundwater impacts); it also suggests a need to examine the extent to which these types of analyses could be biased by typical LUST site monitoring well network layouts. This issue can likely only be resolved through additional detailed characterization at some sites followed by comparison of those data with the results of the comprehensive database analysis.

The database was also used to investigate empirical relationships between LUST site characteristics and groundwater impacts. The following are of particular relevance to risk-based decision-making at LUST sites:

- There was no strong correlation between qualitative geology descriptors and groundwater impacts (similar impacts occurred for all qualitative geologic descriptors).

- There was no strong correlation between depth-to-groundwater and groundwater impacts (similar impacts occurred for all depths to groundwater).

- There was no strong correlation between the distance from deepest soil impacts to groundwater and groundwater impacts (similar impacts occurred for all distances between groundwater and deepest soil impact determined from chemical analysis data).

- Source zone sizes tended to be about eight times larger at sites with free-product detections in wells; however, there was no strong correlation between measured free-product thickness and source zone size (sites with thicker free-product layers did not necessarily have larger source zones).

- There was no strong correlation between chemical concentrations in soil and groundwater impacts; in particular, groundwater impacts were often observed even when contaminant concentrations in soils were below detection levels (i.e., soil concentrations are not reliable measures or indicators of groundwater impacts at LUST sites).

- Quantitative subsurface flow properties cannot be reliably inferred from qualitative geology descriptors found in soil boring logs.

- Impacts to any of the roughly 10,000 municipal/utility wells are only likely to be significant under conditions where at least 10 LUST sites are within the water supply well's capture zone and there is minimal biodegradation of the chemical(s) of concern; a GIS analysis suggests that less than 6% of municipal/utility wells are currently in such settings.

- Impacts to any of the roughly 19,000 domestic wells in Arizona are only likely if the well is in close proximity to, and directly down-gradient, of one or more sites (i.e., 1,000 ft or less) and there is minimal biodegradation of the chemical(s) of concern; a GIS analysis suggests that about 20% of domestic wells are within 1/2 mile of one or more UST sites, but the analysis is unable to determine the fraction located within 1,000 ft and also down-gradient of UST sites; about 2.5% of domestic wells are within 1/2 mile of 5 or more UST sites.

Current risk-based decisions are often predicated on the assumptions that: a) groundwater impacts should be less as the depth-to-groundwater increases, b) the extent of impacts should be less for sites described by finer-grained descriptors (e.g., silts/clays), and c) the impacts are generally greater at sites with higher contaminant concentrations in soils. Observations presented above from the data analyses show these assumptions to not be universally true.

Finally, this study investigated the performance of remediation technologies at Arizona LUST sites, with the intent of identifying relationships between technology performance and LUST setting; however:

- The data were insufficient to draw defensible conclusions concerning the performance or cost-effectiveness of remediation technologies applied at Arizona LUST sites; this is in part a reflection of ADEQ data requirements (closure can be granted based on only two monitoring events and this is insufficient data from a technology evaluation viewpoint), as well as a reflection of the limitations of data collected at many of the remediation sites (e.g., collecting groundwater samples during active remediation system operation). It is also a reflection of the history of LUST activities in Arizona (to date, much effort has been devoted to the initial characterization of LUST sites and less to remediation).

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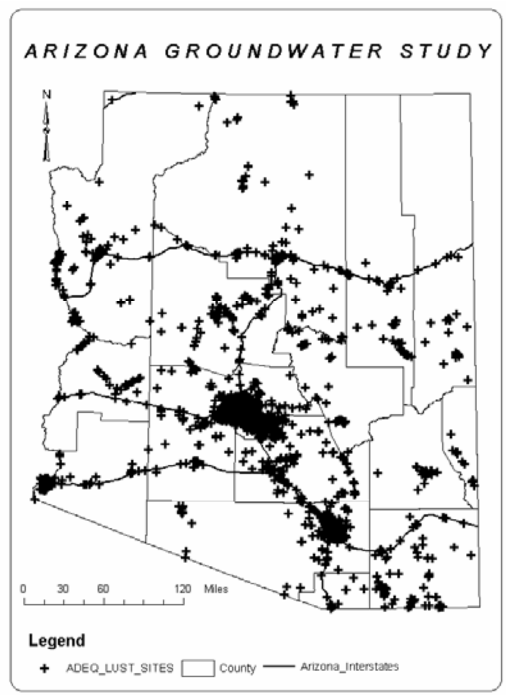
1.0 INTRODUCTION

Gas stations and other facilities in Arizona (and across the United States) store and dispense petroleum fuels through underground storage tank (USTs) systems. Typical gas station UST systems consist of three or more large volume (>5000 gallon) underground storage tanks, a network of underground piping, and dispenser islands. Historically, the decision to use below-ground storage systems was based on public safety concerns; however, we now know that the subsurface environment promotes corrosion, natural stresses in the soil can cause fittings and lines to leak, and subsurface emplacement makes leak detection difficult.

Over the years, and especially recently[1], much effort has gone into upgrading and ensuring the integrity of these systems. However, experience suggests that there may still be past releases that have yet to be detected and that accidental releases will likely continue in the future.

Given the large number of gasoline stations, the frequency of releases, and the potentially harmful nature of some gasoline constituents (e.g., benzene, methyl tert-butyl ether (MTBE), tert-butyl alcohol (TBA)), UST sites have the potential to cause adverse impacts to groundwater resources. Nationwide, there are currently over 700,000 UST sites and there have been over 400,000 confirmed releases[2]. Arizona has had over 9,000 UST facilities on file at the Arizona Department of Environmental Quality (ADEQ). Of these, about 4,300 have attained leaking underground storage tank (LUST) status. The state-wide distribution of LUST sites is shown in Figure 1; these tend to be concentrated along major roadways and in cities and towns.

Figure 1. Distribution of LUST Sites in AZ.



With such widespread UST distribution and the potential for adverse impacts to groundwater, the Arizona Groundwater Study was commissioned by the Arizona State Legislature to study LUST impacts to groundwater resources in Arizona. It was felt that a comprehensive look at the nature of LUST impacts to groundwater state-wide would help guide future cost-effective and protective management of LUST sites. This study was directed by the Underground Storage Tank Policy Commission, the contracting was administered by ADEQ, and the study was conducted by

[1] - the 12/22/98 federally-mandated UST upgrade deadline.
[2] - U.S. EPA. 2002. *UST Program Fact – Summary.* Office of Solid Waste and Emergency Response, United Stated Environmental Protection Agency, Washington, D.C. September 2002. http://www.epa.gov/oust/pubs/ustprogramfacts.pdf

Arizona State University (ASU) in full cooperation with ADEQ, the UST Policy Commission, UST site owners and operators, and environmental consulting firms that deal with LUST site issues.

2.0 BACKGROUND - OTHER STATE-WIDE LUST STUDIES

Until recently, LUST sites were studied on a case-by-case basis, and little effort was made to compile data and draw conclusions from the results of thousands of LUST site characterizations and cleanups that had been completed. In the past eight years a few key empirical studies have been completed. These include the Lawrence Livermore National Laboratory studies[3,4], the University of Texas study[5,6], and the USGS nation-wide survey of VOC impacts to groundwater[7]. The first two focused on impacts in the vicinity of LUST sites in California and Texas, and involved review and compilation of data from LUST reports submitted to regulatory agencies in those states. A study of LUST site impacts in Florida[8] has also been conducted, but those results are less relevant to this study given the extreme dissimilarities in hydrogeological conditions.

The California and Texas LUST studies emphasized the spatial distributions of a few major gasoline constituents in groundwater, including MTBE and BTEX (benzene, toluene, ethylbenzene, and xylenes). In all studies, the spatial extent of contamination was characterized in terms of a "plume length" defined to be the distance down-gradient of a release where concentrations decreased to less than concentrations of concern (i.e. 10 ug/L benzene in the Texas study). In two of the studies, plume lengths were determined by fitting available dissolved concentration data to simplistic mathematical chemical fate and transport equations, and then predicting the down-gradient distance to the target concentration. In the third study, the plume lengths were determined more subjectively, based on a visual interpretation of the data.

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[3] - Rice, D.W., R.D. Grose, J.C. Michaelson, B.P. Dooher, D.H. MacQueen, S.J. Cullen, W.E. Kastenberg, L.G. Everett, and M.A. Marino. 1995. *California Leaking Underground Fuel Tank (LUFT) Historical Case Analysis*; Environmental Protection Department, Environmental Restoration Division, Lawrence-Berkely Laboratories, UCRL-AR-122207.

[4] - Happel, A.M., E.H. Beckenbach, and R.U. Halden. 1998. *An Evaluation of MTBE Impacts to California Groundwater Resources*. Environmental Protection Department, Lawrence Livermore National Laboratory. UCRL-AR-130897.

[5] - Mace, R.E., C.I. Mayfield, and J.F. Barker. 1997. *Extent, Mass, and Duration of Hydrocarbon Petroleum Storage Tank Sites in Texas.* Bureau of Economic Geology, University of Texas at Austin, Geological Circular 97-1.

[6] - Mace, R.E., and W.J. Choi. 1998. *The Size and Behavior of MTBE Plumes in Texas*. Proceedings of the 1998 API / NGWA Petroleum Hydrocarbons in Groundwater Conference, Houston TX, November 11-13.

[7] - Squillace, P.J., M.J. Moran, W.W. Lapham, C.V. Price, R.M. Clawges, and J.S. Zogorski. 1999. *Volatile Organic Compounds in Untreated Ambient Groundwater of the United States, 1985-1995.* Environmental Science & Technology 33. no.*5: 1712-1730.*

[8] - Reid, J.B., H.J. Reisinger, II, P.G. Bartholomae, J.C. Gray, and A.S. Hullman. 1999. *A Comparative Assessment of The Long-term Behavior of MTBE and Benzene Plumes in Florida, USA*. In Natural Attenuation of Chlorinated Solvents, Petroleum Hydrocarbons, and Other Organic Compounds (1), ed. B.C. Alleman and A. Leeson, 97-102, Battelle Press, Columbus, OH.

The California and Texas studies concluded that dissolved benzene would travel only short distances before being attenuated to concentrations below levels of concern; in the California study it was stated that dissolved benzene plume lengths rarely exceed 250 ft (based on a 10 ug/L contour). It was reported in the Texas report that 75% of dissolved benzene plumes have lengths of less than 250 ft (again, based on a 10 ug/L contour). Through temporal analysis of the data, these two studies also concluded that most dissolved plumes are stable (i.e., not growing) or are shrinking (i.e., decreasing in concentration). The California MTBE study reported that dissolved MTBE plumes tend to be similar in size to benzene plumes, but cautioned that this may be an artifact of the more recent use of MTBE, and that dissolved MTBE plumes might extend to greater distances in the future. The Texas study also concluded that most MTBE plumes tend to be stable and similar in size to benzene plumes, but cautioned that the conclusions might be specific to the clayey fine-grained soil sites that dominated the Texas database. When considering these conclusions concerning the relative lengths of MTBE and benzene plumes, one needs to also consider that there are other well-known sites where MTBE plumes are much longer than their associated BTEX plumes (e.g., Santa Monica, CA; Port Hueneme, CA; Vandenberg Air Force Base; etc.) and in some cases municipal well-fields have been impacted; furthermore, the reason for this behavior at some sites and not at others is not well-understood at this time.

The U.S. Environmental Protection Agency (USEPA) has cautioned over-generalization of the results from these studies, as they are specific to the types of sites used in those studies. For example, both the Texas and California studies are biased towards shallow groundwater in finer-grained settings. Arizona, on the other hand, sits above deeper aquifers and coarser-grained soils.

The chemicals studied in the California and Texas reports included the BTEX and MTBE compounds, primarily because the BTEX constituents have traditionally been compounds of concern in LUST regulatory programs and because MTBE has recently received attention because of its national use as a fuel additive, its widespread occurrence in groundwater, and impacts to some drinking water supply wells. However, in addition to these constituents, hundreds of other fuel-related chemicals also dissolve into groundwater at LUST sites, and existing data for those constituents are limited. For example, because of their chemical properties and proportions in fuels, other chemicals expected to occur at significant concentrations in groundwater include: alcohols (methanol, ethanol, TBA, etc.), alkyl ethers (MTBE, ETBE and DIPE), and other aromatics (i.e., the trimethylbenzenes and naphthalene). Understanding the concentrations and the frequency of occurrence of these chemicals would be valuable to better understand the potential impacts from gasoline releases to groundwater resources and the water quality at nearby wells.

3.0 ARIZONA GROUNDWATER STUDY OBJECTIVES

The primary objective of the Arizona Groundwater Study was to conduct a study of LUST impacts to groundwater resources in Arizona, with the hope that the results would help guide cost-effective and protective management of LUST sites. Prior to conducting the study, the following tasks were identified by stakeholders (i.e., ADEQ, owners/operators, consultants, public) to be desirable components:

- A determination of the nature and extent of regulated substances and other contaminants of concern released from LUSTs in hydrologically similar study areas throughout the State (excluding Indian Lands). The Study Areas shall include, at a minimum, the following physiographic regions: Basin and Range, Colorado River, Colorado Plateau, and the transition zones including mountains.

- An evaluation of the general risks posed by LUST releases to natural resources and receptors within the areas identified above. Neither a comprehensive health-based risk assessment nor an ecological risk assessment is the objective of this study.

- An evaluation of the relative and relevant corrective action costs associated with various remedial and monitoring strategies, including the feasibility of such strategies, and the costs associated with resource and receptor protection.

Upon consideration of this stakeholder input, technical objectives defined by the ASU Study Team included the following:

- A characterization of the data typically available for Arizona LUST site decision-making

- A characterization of the hydrogeologic conditions at Arizona LUST sites

- A characterization of the extent of soil impacts at Arizona LUST sites

- A characterization of the extent and magnitude of groundwater impacts at Arizona LUST sites

- A characterization of the occurrence of regulated and some previously non-regulated chemicals of potential interested at Arizona LUST sites (i.e., MTBE, TBA, alcohols, trimethylbenzenes, etc.)

- A characterization of the data available from LUST site cleanups and an evaluation of the relationships that exist between site characteristics, clean-up technology, performance and cost.

- Evaluation of any relationships that exist between site characteristics and LUST site impacts

- A characterization of the relationships between LUST site locations, drinking water supply wells locations, and magnitudes of potential impacts to groundwater quality in the supply wells

4.0 METHODOLOGY

The Arizona Groundwater Study was accomplished through the following sequence of activities:

a. Review of more than 400 Arizona LUST site reports on-file at ADEQ, and compilation of data from those reports

b. Collection of supplemental data to fill data-gaps identified in (a), including:

   - additional groundwater sample collection and analysis
   - aquifer characterization testing
   - assessment of survey and groundwater-level measurements errors
   - supplemental site characterization activities at select facilities

c. Empirical analysis of the combined (existing + supplemental) data set, and

d. A combined theoretical-spatial (GIS) analysis focused on identifying LUST scenarios posing the greatest threats to use of groundwater resources.

Each of these is addressed below in more detail.

4.1 FILE REVIEW AND DATA COLLECTION

Data were obtained from the review of 417 Arizona LUST files, and included general site characteristics, hydrogeology, well completion data, and groundwater and soils data for each site.

4.1.1 Site Selection

Site selection was based on the following:

- Geographic and Geologic coverage - Sites were selected to provide good geographic coverage across the state and also representation of the major geologic provinces of Arizona.

- Historical MTBE concentration data - until recently MTBE concentrations in groundwater have not been regulated or routinely monitored in Arizona; thus, emphasis was placed on identifying sites having historical MTBE data.

- Sites determined by ADEQ to not warrant further corrective action (these sites are referred to as “Closed” sites in this report). Closed sites were selected in anticipation that these would be the most likely to provide information on successful clean-up approaches and costs.

- Sites with past or ongoing remediation - to provide data on remedial technology selection, performance, and cost.

- Sites with natural attenuation monitoring plans - to look at its effectiveness over time, and to understand its potential as a remedial alternative.

- Sites accessible for supplemental data collection - these primarily included ADEQ State-Lead and Conoco-Phillips (Formerly TOSCO - Circle K and Union 76) sites.

Sites with excessively large files that could not be analyzed in a timely fashion, sites with multiple source zones that led to co-mingled and non-distinct plumes, or sites with readily apparent data quality problems were avoided. Tools used in site selection included the ADEQ USTrack database, the ADEQ MTBE database, a listing of ADEQ State Lead sites, and industry site lists.

4.1.2 Information Collected from LUST Files

Table 4.1 lists the type of information compiled during the LUST file reviews.

4.1.3 File Review, Information Collection, and Data Quality Management

Some of the information listed in Table 4.1 was extracted directly from the reports (i.e., facility address, etc.), while other information (i.e., direction of groundwater flow, source zone size and location, etc.) required varying levels of interpretation. Rules established for data interpretation are provided in Appendix A, and they are also discussed briefly throughout the remainder of this report, at appropriate points. *It is important to note that the professional judgment of the ASU team played a role in the data gathering, and that file interpretation was performed independent of conclusions contained in the LUST file reports.*

Information recorded from ADEQ files was first entered by hand on pre-formatted data log sheets and then was entered in an electronic database. Photocopies of key information for each site were made at the time of review and placed in an archive file. Key information included depth-to-water data, potentiometric surface maps, historic groundwater and soils data, borehole logs, site maps, interpretive maps showing source zone, plume dimensions, and monitor well and borehole locations, and supporting text which aided in site characterization.

The data were hand-written in data log sheets, and then transferred to an electronic database. The data log sheets and corresponding rules for data reduction, data entry, and quality control are discussed briefly below and in more detail in Appendix A.

Validation of the information provided in the LUST file reports was not performed. Occasionally, inconsistencies and errors would be noted across reports for the same site and attempts would be made to reconcile those inconsistencies to the extent practicable. Also, it should be noted that the file review was limited to documents in each site's file at the time of review. When missing documents could not be found, a decision was made whether or not to proceed with that site's file review, based on the completeness of the available data.

Table 4.1. Data Log Sheet Entries.

General Site Information ADEQ Facility ID and LUST ID Facility Name, Address Site Status: Open/Closed Location: Township/Range/Section Geographic Setting Setting Relative to other USTs Setting Relative to Sensitive Receptors Site Dimensions **General Site Characteristics** Spill Description: year discovered type of product, volume lost date of tank removal point of release, single/multiple release Spill Location: distances between UST system center, down-gradient boundary, source zone center, and down-gradient source zone boundary Monitor Wells and Hydropunches: total number number in source zone number up-/down-/cross-gradient Soil Borings: total number number in/out of source zone Remediation: type and status total volume and free-product volume removed **Well Completion Data** Location coordinates relative to source zone center and UST system center Relative Position up-/down-/cross-gradient of source zone Screened Interval Submergence Free-product presence	**Hydro-geological Conceptual Model** Topography and Vegetation Geologic Descriptors: unconsolidated vs. consolidated qualitative vadose and saturated zone descriptors (interbedded sand/silts/clays, sands and gravels, silts and clays, etc.) Flow Direction: range of flow direction from water level data range of flow direction from all data plume orientation Gradient Hydraulic Conductivity Depth-to-Water and Water Table Elevation Water Table Fluctuation Characteristics Presence Within Larger-Scale/Regional Impacts **Groundwater Data** BTEX, TPH, and MTBE Dissolved Concentrations pre- vs. post-remediation data representative low concentration representative high concentration temporal trends number of sampling events Water Level vs. Dissolved Concentration Relationship Other EPA Method 8260 Analytes in Source Zone **Soils Data** Soil Boring Data total sampling depth number of samples sent for chemical analysis boring depth relative to saturated zone depth presence of stains/odors and the depths they occur co-located monitor well identification BTEX, TPH, and MTBE Detections Benzene, TPH, MTBE Data maximum depths detected when greater than specified concentrations maximum concentration at or below water table maximum concentration and the associated depth Relative Location of Borehole in/out of source zone

Data quality control measures were instituted to ensure the accuracy and consistency of data extracted from the ADEQ files and entered in the electronic database. The review process is outlined in Table 4.2. To minimize inconsistencies, the entire file review was conducted by two file reviewers.

To minimize electronic data entry errors, all data entries were performed by a single database manager. Accuracy of database entries was managed by three iterations of database queries designed to check omissions, consistency across entries, and data entry accuracy. Following the database queries, a random selection of 15% of the files entered was checked item-for-item. Errors which had the potential to change the outcome of a query were noted at 84 per 56,388 entries or an error of <0.15% (considered excellent).

Table 4.2. Data Quality Management Review Process Summary.

Quality Management Component	Definition	Frequency (total)	Basis For* Frequency
Joint Review	Joint review of source zone delineation and plume movement by file review team members to encourage consistent and accurate interpretive skills.	1-in 4 (83)	335 sites in database
Review Duplicate	Duplicate file reviews were performed by the other file review team member as a check for data accuracy and consistency of interpretation throughout a file. Duplicate reviews focused on soil and groundwater data, flow direction and gradient, source zone delineation, and plume trace.	1-in-25 (10)	249 GW impacted sites
Primary Investigator Interpretation	On an as needed basis, questions concerning any component of file interpretation that could not be answered by file review team members were answered by the primary investigator (PI). This provided a point of comparison for the review team as well as a basis for future decisions.	1-in-6 (61)	335 sites in database
Primary Investigator Interpretive Check	Brief review of source zone delineation, flow direction, and plume trace by the PI to ensure interpretations were reasonable and consistent with those of the PI.	1-in-10 (25)	249 GW impacted sites
Primary Investigator Review Duplicate	Duplicate file reviews were performed by the primary investigator as a check on accuracy of interpretation throughout a file. PI duplicate reviews focused on soil and groundwater data, flow direction and gradient, source zone delineation, and plume trace.	1-in-42 (6)	249 GW impacted sites

* Quality management only for the 335 files entered in the database

4.2 SUPPLEMENTAL DATA COLLECTION

4.2.1 Supplemental Groundwater Sampling and Analysis

Supplemental groundwater samples were collected and analyzed to assess the occurrence of the petroleum fuel constituents not typically reported in LUST files. The list of analytes also included the BTEX constituents:

- Benzene
- Ethylbenzene
- Toluene
- m,p-xylenes
- o-xylenes
- Naphthalene
- MTBE
- ETBE
- DIPE
- TBA
- Methanol
- Ethanol
- 1,2,3 trimethylbenzene
- 1,2,4 trimethylbenzene
- 1,3,5 trimethylbenzene
- Isopropanol
- n-propanol
- n-butanol

In the first phase of this work, consultants provided samples to ASU for analysis. During the course of 86 routine sampling events across 50 LUST sites, a total of 452 groundwater samples were collected. Of the 50 LUST sites, 42 were classified as “gasoline-contaminated” sites based on available site and release-history data.

These samples were analyzed by a head-space gas gas-chromatography method using flame-ionization and photo-ionization detectors (GC-FID/PID); however, it became apparent that there was a lack of resolution in the analysis of TBA and high detection levels for alcohols. This led to a transition to a heated purge-and-trap gas chromatography with mass spectrometry detection. (GC-MS). As a result, an additional 256 no-purge groundwater samples and 30 free-product samples were collected from 36 sites by the ASU team.

Complete details of the analytical methods and results are contained in Appendix B.

4.2.2 Aquifer Characterization Tests

Aquifer characterization tests (slug tests) were performed using a total of 32 wells across 11 sites; sites were selected to provide an initial assessment of aquifer properties across a range of aquifer materials.

4.2.3 Monitoring Well Survey and Depth-to-Water Measurement Errors

Surveys of monitoring wells were conducted by two different methods (spirit-level and GPS methods) at each of 17 sites. Differences in surveyed elevations between the two methods were assessed as well as differences between recent survey results and survey data in the file reports.

Depth-to-groundwater in monitoring wells was measured at each of six sites by two to three people using two different water level sensors (both sensors used by each person); the purpose was to determine the potential error in groundwater elevation determination stemming from depth-to-groundwater measurement errors.

4.2.4 Additional Site Characterization Efforts

Six sites were chosen for additional characterization work with the hope that the data from these sites could be presented as being representative of the larger population of LUST sites. Activities at these sites generally focused on the installation of temporary groundwater sampling points and the collection and analysis of groundwater samples from those points and all existing groundwater monitoring wells.

5.0 RESULTS

The organization of this section is intended to follow a logical progression, where successive sections build on results and information presented in preceding sections; *thus it is important to review the results in the sequence that they are presented.* For example, one must understand the nature of LUST site sampling (i.e., numbers of samples per site, typical arrangements of sampling locations, sampling limitations, etc.) in order to properly interpret the chemical distribution information.

The frequency, or number of times, a given condition was encountered in the database is presented throughout the text (e.g., "249 of 335 sites had measured groundwater impacts above Arizona regulatory standards"). *It is important not to interpret this to mean that this is the frequency at which this condition occurs when considering all sites in Arizona.* A random selection process was not used to select the files reviewed in this study, and therefore, the site selection criteria could have introduced biases to the database. In addition, the regulatory process introduces biases and these affect the types and numbers of total LUST files available for review.

5.1 CHARACTERIZATION OF THE ADEQ LUST FILE ANALYSIS EFFORT

As summarized in Table 5.1, 417 ADEQ LUST files were reviewed. The electronic database contains information for 324 of the 417 files. Data from the remainder of files were deemed not suitable for entry in the electronic database. The 324 files represented in the database translated to 335 LUST site entries because nine files had more than one distinct release location.

Sites in the database were characterized by the type of data available and the impacts suggested by that data. Table 5.2 shows those characterizations.

Table 5.1. Distribution of Files Analyzed During this Study.

Number of Files Reviewed	Description
324	Files with data suitable for database entry. Nine (9) files/facilities included more than one distinct point of release, providing a total of 335 sites for the database.
2	Groundwater sites a) One was a duplicate file for a site already analyzed b) One was merged with another site due to source zone and plume characteristics
8	Sites part of the Willcox Area-Wide Investigation a) One file was the Willcox Area-Wide master file b) Seven files are individual sites part of the area-wide investigation, none of which have enough data for an individual site assessment
46	Data Log Sheets completed but no post-discovery soil or groundwater data available for site
37	File reviewed but no Data Log Sheet filled out a) 18 sites with little to no data available b) 9 sites with questionable and/or poor data c) 3 files too large to perform a reasonable review d) 2 files with missing reports e) 5 files did not fit criteria of study at the time file was reviewed

A total of 417 files were reviewed

Table 5.2. Categorization of Database Sites Based on Measured Impact to Soils and Groundwater.

General Site Type	Number of Sites	Acronym	Description
Groundwater Data Available	249	- GW - groundwater	Sites with impacted groundwater, and concentrations exceed Arizona groundwater standards or free-product is present.
	15	- GWU - groundwater undetermined	Sites where available groundwater data shows negligible impact, however, there is reason to suspect more significant impacts. For example, a heavy soils impact is observed at or near the water table, groundwater sampling locations or frequency are insufficient to reasonably demonstrate impact, or minor groundwater impacts are likely associated with off-site source.
	10	- SOV - soils only verified	Sites with impacted soils and sufficient groundwater data to reasonably argue that there is no indication of groundwater impact.
Groundwater Data Not Available	26	- SOU - soils only unverified	Only soils data is available and it suggests that the soils impact does not appear to extend to groundwater.
	34	- SOIL - only soils data available needs further characterization	Only soils data was available and further characterization is needed to determine if groundwater is impacted.
	1	- NA - not analyzed	Site not fully analyzed but was maintained as database entry since site had fractured consolidated sediments.

Total number of sites in database – 335

Sites in the database can also be characterized by their spatial distribution as is done in Figures 5.1 and 5.2 and Tables 5.3 and 5.4. The distribution of sites across Arizona includes all 15 counties (Table 5.3), 116 cities/municipalities (Table 5.4), 152 zip codes, and 134 township/ranges.

Figure 5.1. LUST Site Files Reviewed in this Study.

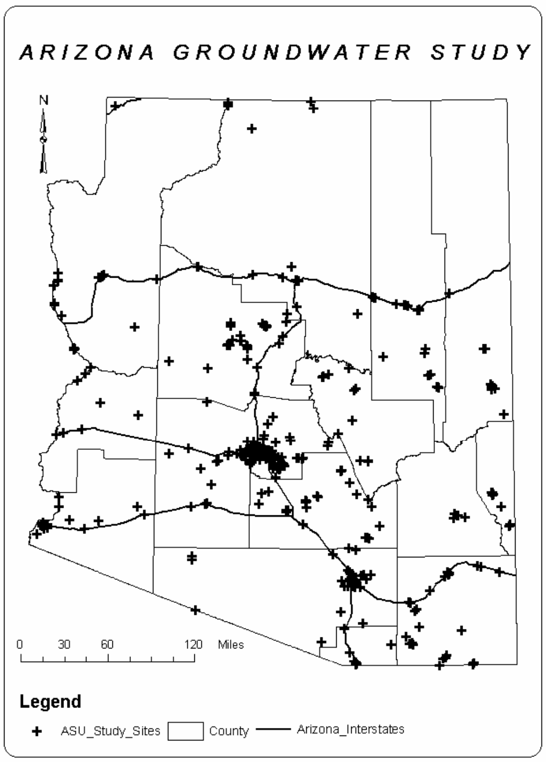
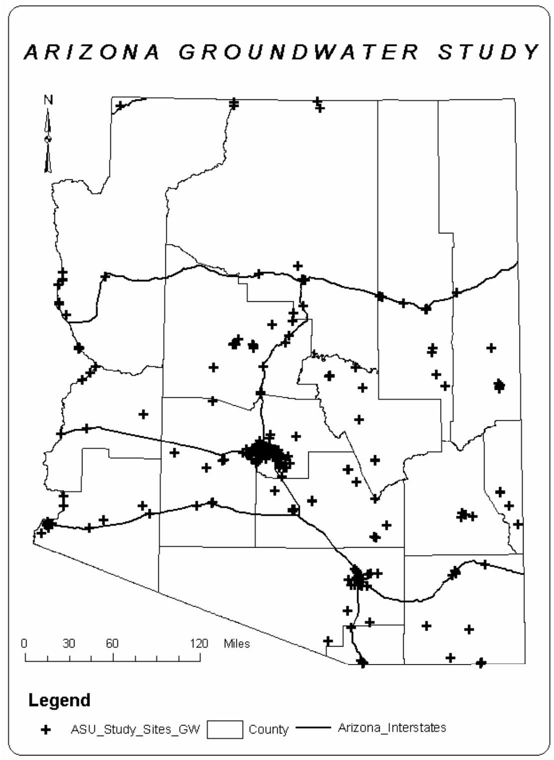


Figure 5.2. LUST Site Files Reviewed with Groundwater Impacts.



Sites are distributed across all three geologic provinces of Arizona: These are the Basin and Range (BR), the Central Highlands or Transition Zone (Tr), and the Colorado Plateau (CP). Their distribution, along with the addition of the Colorado River basin through western Arizona (CO)(herein referred to as a geologic province also), is shown in Table 5.4 as a function of city.

The study focused on both open and closed sites. Of the 335 sites in the database, 277 sites (83%) remain open while 58 have been closed (i.e., ADEQ has decided that no further corrective action is necessary at this time).

Table 5.3. Distribution of LUST Site Files Reviewed by County.

County	Number of Sites	County	Number of Sites	County	Number of Sites
Apache	9	Greenlee	5	Pima	30
Cochise	23	La Paz	10	Pinal	26
Coconino	16	Maricopa	113	Santa Cruz	5
Gila	12	Mohave	13	Yavapai	28
Graham	7	Navajo	23	Yuma	15

Total number of sites - 335

Table 5.4. Distribution of LUST Site Files Reviewed by Town/City and Geologic Province.

City	Glg* Prov	# Sites	City	Glg* Prov	# Sites	City	Glg* Prov	# Sites
Ajo	BR	1	Fredonia	CP	3	Rimrock	Tr	1
Amado	BR	1	Gila Bend	BR	4	Riviera	CO	1
Apache Junction	BR	2	Gilbert	BR	2	Rock Springs	BR	1
Arivaca	BR	1	Glendale	BR	6	Roll	BR	1
Arlington	BR	1	Globe	BR	4	Roosevelt	BR	1
Avondale	BR	2	Goodyear	BR	5	Safford	BR	2
Benson	BR	3	Green Valley	BR	2	Saint David	CP	1
Bisbee	BR	1	Harquahala Valley	BR	1	Saint Johns	BR	3
Black Canyon City	Tr	1	Hayden	BR	3	Scottsdale	BR	3
Bouse	BR	1	Heber	CP	1	Sedona	Tr	2
Bowie	BR	2	Holbrook	CP	6	Show Low	CP	2
Buckeye	BR	3	Humboldt	Tr	1	Sierra Vista	BR	2
Bullhead City	CO	3	Joseph City	CP	3	Snowflake	CP	1
Camp Verde	Tr	2	Kearny	BR	1	Solomon	BR	1
Carefree	BR	1	Kingman	BR	2	Somerton	CO	1
Casa Grande	BR	4	Lake Havasu City	CO	3	South Tucson	BR	2
Cashion	BR	1	Laveen	BR	3	Springerville	CP	2
Catalina	BR	1	Littlefield	BR	1	Star Valley	Tr	1
Cave Creek	BR	1	Mammoth	BR	1	Sun Lakes	BR	1
Chandler	BR	4	Marana	BR	1	Superior	BR	2
Chino Valley	Tr	1	Maricopa	BR	2	Taylor	CP	2
Christopher Creek	Tr	1	Martinez Lake	CO	1	Tempe	BR	10
Clarkdale	Tr	1	Mayer	Tr	1	Thatcher	BR	4
Clifton	Tr	2	Mesa	BR	4	Tolleson	BR	2
Coolidge	BR	4	Miami	BR	1	Tonopah	BR	1
Cordes Junction	Tr	1	Mohave Valley	CO	2	Topock	CO	1
Cottonwood	Tr	3	Munds Park	CP	2	Tucson	BR	22
Dateland	BR	2	Nogales	BR	4	Wellton	BR	1
Dewey	Tr	2	Oracle	BR	2	Wenden	CO	2
Douglas	BR	3	Page	CP	3	Wickenburg	BR	1
Duncan	BR	3	Parker	BR	3	Wikieup	BR	2
Eagar	CP	2	Payson	Tr	4	Willcox	BR	9
Ehrenberg	CO	2	Petrified Forest	CP	1	Williams	CP	2
Elfrida	BR	1	Phoenix	BR	55	Winkelman	BR	1
Eloy	BR	2	Pinetop	CP	4	Winslow	CP	5
Fairbank	BR	1	Prescott	Tr	7	Yarnell	BR	1
Flagstaff	CP	5	Prescott Valley	Tr	2	Young	Tr	1
Florence	BR	1	Quartzite	BR	1	Yuma	CO	9
Fountain Hills	BR	2	Randolph	BR	1			

* Geologic Provinces: Basin and Range (BR), Transition or Intermountain Region (Tr), Colorado Plateau (CP), Colorado River (CO)

5.2 LUST SITE REGIONAL AND LOCAL SETTINGS

Table 5.5 summarizes geographic and topographic descriptors of the settings in which the sites reviewed are located.

Table 5.5. Geographic and Topographic Setting for Site Files Reviewed.

Geographic Setting		Number of Sites	Terrain	Number of Sites
Broad Basin		190	Flat/Mild	247
Confined Valley		7	Moderate	85
Foothills		16	Steep	1
High Plateau		32	Unknown	2
Mountainous		55		
Other:	• CO River Valley	25		
	• Gila River Valley	5		
	• San Pedro River Valley	2		
	• Plateau over CO River Valley	1		
Unknown		2		

Total number of sites - 335 sites

Other relevant characteristics of the LUST site settings include the following:

- 281 (84%) sites were located in areas where both industrial/commercial and residential areas were found within 1/4 mile of the site. Forty-six (46) sites were in solely industrial/commercial areas and 8 were in residential, agricultural, or park settings.

- 242 sites were subjectively described as urban/suburban, and 93 were considered rural.

- 33 (10%) sites were known to be located within a larger impacted groundwater region (WQARF or EPA Superfund), while 120 (36%) were known not to be. Insufficient information was available for the remainder of the sites (54%).

- The LUST sites reviewed varied in size from small service station facilities to large mining operations. This variation resulted in a wide array of property sizes. Fifty percent (50%) of the sites had dimensions of 190 feet by 150 feet (28,500 sq. ft.) or less.

- Information on the number of other UST sites within 1/4 mile of a given LUST site was available for only 25% of the sites listed in the database; for those sites, the mean number within 1/4 mile was three and the maximum was 16.

- Information on the presence of groundwater receptors (specifically production wells) within 1/4 mile of a given LUST site was available for 199 (59%) of the sites listed in the database. Of those reporting the presence of groundwater receptors within 1/4 mile, a mean of five (5) and a range of zero (0) to 53 was noted, however, the numbers reported for each site may not have been inclusive of all wells that actually exist within that radius. Files for 110 (33%) sites provided a minimum distance to groundwater receptors with distances ranging from 0 to 6,600 feet.

- A supplemental analysis of groundwater production wells and their proximity to LUST sites involved the use of the Arizona Department of Water Resources Well Registry Database. A Geographic Information Systems (GIS) analysis was performed to determine the number of production wells within 1/4 mile of the LUST sites reviewed in this study. Only production wells not flagged as abandoned and which were specified as either *municipal* or *utility* wells were considered. The number of wells within 1/4 mile of a LUST site varied from zero (0) to five (5). A total of 81 of the LUST facilities included in this study had at least one (1) production well within 1/4 mile. The distance from each LUST site to the nearest production well was also determined. The mean distance between the LUST facilities and the nearest production well was 11,000 feet, with a range of 128 to 300,000 feet and a standard deviation of 23,000. A more detailed GIS analysis involving all UST sites is presented later in this report.

- Eighty-two (82) sites (24%) listed other receptors of concern, including rivers, creeks, canals, and lakes. Distances to these ranged from 20 to 5500 feet with a mean distance of 1336 feet.

5.3 TYPES OF RELEASES AT LUST SITES

The majority of sites were impacted by gasoline releases. Of the 335 sites, 211 reported only gasoline releases, while most of the other sites had releases of gasoline and one or more other hydrocarbon mixtures (i.e., diesel, waste oil, etc.). Table 5.6 shows the distribution of types of releases for the sites reviewed.

The exact volume of product released at a site is typically unknown. Only 16 sites (5%) reported an estimated volume of release, with a mean of 8,353 gallons and a reasonably uniform distribution across a range of 25 to 39,000 gallons.

Table 5.6.
Types of Releases at the LUST Sites Reviewed.

Type of Hydrocarbon Released	Number of Sites
Gasoline	211
Gasoline, Diesel	65
Gasoline, Waste Oil	25
Diesel	17
Gasoline, Diesel, Waste Oil	4
Waste Oil	2
Gasoline, Diesel, Waste Oil, Other (asphalt chemicals)	2
Gasoline, Other (kerosene)	1
Gasoline, Other (petroleum distillates – unspecified)	1
Gasoline, Other (pre-mix oil and gasoline)	1
Gasoline, Diesel, Other (heating oil)	1
Other (aviation fuel)	1
Other (jet fuel)	1
Other (solvents / mineral spirits)	1
Other (unknown)	2

Total number of sites - 335

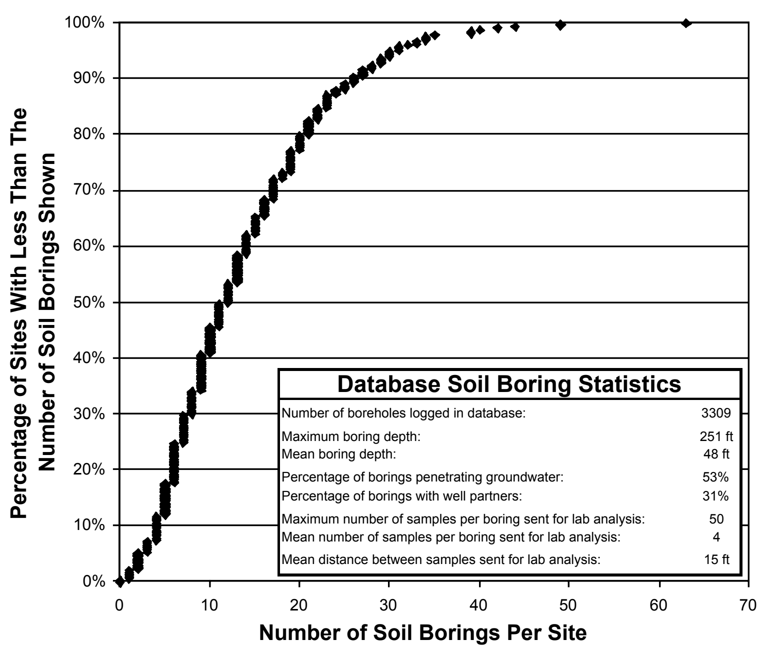
This study did not attempt to identify the date of initial release nor the duration of the release, because these are typically unknown. When possible, the date the UST site began operation and the date the spill was originally reported/discovered were recorded in the database. Most (87%) of the release reports were made during the 1988 to 1998 time frame, a period coincident with the federally mandated UST upgrade regulations, the deadline for which was December, 1998. Of the 98 sites (29%) with known dates of initial operation, 95 began prior to 1988. Roughly half (53%) of sites reviewed began operation prior to 1970, with the earliest beginning in 1934.

The study initially attempted to determine the number of releases for a given site. Though this information was difficult to assess, information was recorded regarding whether multiple LUST numbers had been assigned to a given facility. Multiple LUST numbers could be indicative of multiple release events and/or releases that occurred in multiple locations within the UST system (tanks, lines, dispensers, etc.). Based on LUST numbers, 50% of the sites reviewed indicated single releases, 46% indicated multiple releases, and 4% were unknown.

All major portions of, and operations associated with, UST systems appear to be susceptible to failure. Points of release noted in this study included tanks, lines, dispensers, waste-oil tanks, and surface spills during tank filling. Tanks were the most commonly noted point of release (80% of sites reviewed). Releases from lines and dispensers were noted for 39% and 23% of all sites reviewed, respectively. Waste-oil releases and/or surface spills were noted for less than 4% of sites.

5.4 SUMMARY OF LUST SITE CHARACTERIZATION ACTIVITIES

Figure 5.3. Summary of Soil Boring Information - Number of Soil Borings Per Site With Data Useful For Source Zone Delineation. (333 sites - 4518 soil borings)



A typical site characterization involves a review of historical activities, a visual inspection of the facility and surrounding area, and the sampling of soils and groundwater. It is common to begin a field investigation by drilling a soil boring adjacent to the suspected point of release. If hydrocarbon-impacted soil is found, additional borings are conducted to delineate the extent of the impacted soils. Some of these soil borings may be utilized for the installation of groundwater monitoring wells for the determination of the depth to groundwater, the direction of groundwater flow, and the extent of groundwater contamination. Consultants hired by the responsible parties typically manage the investigations, and it is not uncommon that several consultants might be used throughout a site's history.

5.4.1 Number of Soil Borings and Soil Samples

For the 335 LUST sites represented in the database, a total of 4,518 soil borings were identified. The distribution of the number of boreholes per site is shown in Figure 5.3; approximately 60% of the database sites had 10 or more soil borings. Data from 3,309 of those soil borings were logged in the database. The mean total depth of a soil boring was 48 feet, and on average four (4) samples per boring were sent for lab chemical analysis. In addition, 1,014 (31%) of the soil borings logged had a "well partner" - a groundwater sampling point within 10 ft of the soil boring. Groundwater data from the "well-soil boring partners" is used later in this report to examine relationships between contaminant concentrations in soils and groundwater.

Boreholes for which no borehole log was included in the LUST file, or logs that contained no useful information regarding petroleum impacts to soil, were not tracked in this study; therefore, the numbers of boreholes may not reflect the actual number of boreholes drilled at the sites reviewed.

5.4.2 Number of Monitoring Wells and Their Placement

The number of groundwater monitoring wells installed at each site studied was also recorded. Of the 335 sites logged in the database, 270 sites had one or more groundwater monitoring wells. Information from a total of 1,850 groundwater monitor wells was logged in the database.

Figure 5.4. Number of Monitoring Wells Installed at the LUST Sites Studied.
(1,850 wells from 270 sites with at least one monitoring well).

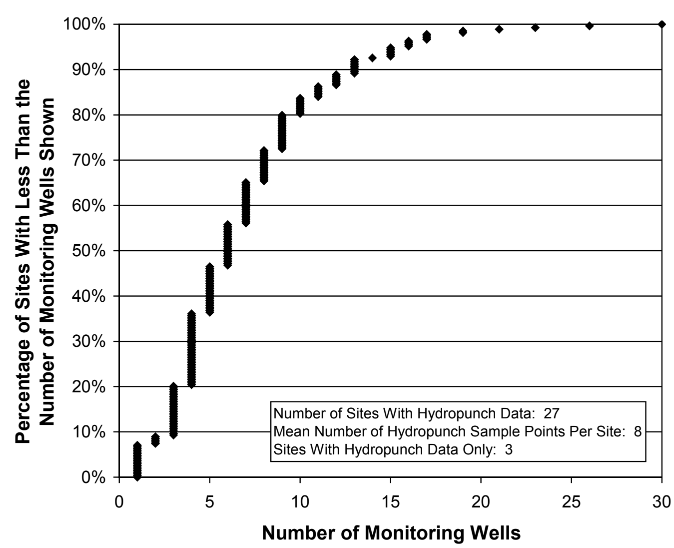


Figure 5.4 and Tables 5.7 and 5.8 characterize the monitoring well information. In brief:

- Figure 5.4 shows that greater than 50% of the sites studied had six (6) or more groundwater monitoring wells, with a maximum number of 30.
- The well screen intervals ranged from three (3) to 97 feet, with 90% of wells having less than 45 ft of well screen as shown in Table 5.7.
- Screen submergence (the condition in which the water table rises above the top of the screened interval) occurred at 78 sites (29%) and in 242 (13%) of the monitoring wells having at least one groundwater elevation measurement. The range of screened intervals for sites with submergence is also given in Table 5.7.

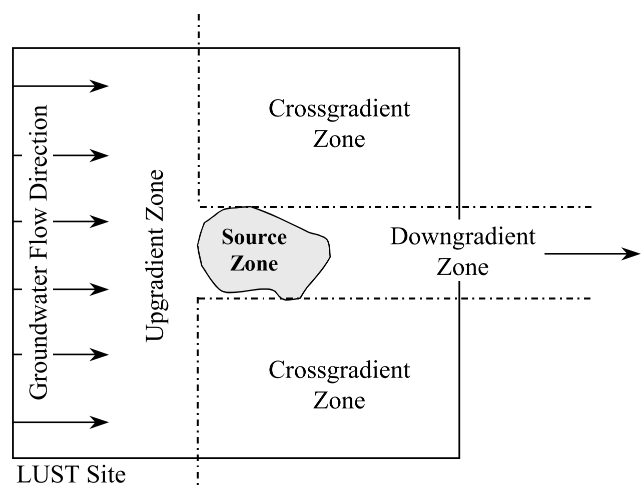
- Distances to the monitoring well located the greatest distance from the UST system center for each site are summarized in Table 5.8. This provides some indication of how far-reaching the groundwater investigations were at the sites studied. Based on the data gathered, half the sites had investigations that were limited to within 200 ft of the UST system center, and 90% of sites had investigations that were limited to less than 610 feet from the UST system center.

Table 5.7. Well Screen Interval Lengths and Frequency of Screen Submergence.

Length of Screened Interval	Number of Monitoring Wells with Screened Intervals of Given Length	Number of Monitoring Wells with Screened Intervals of Given Length and Submergence on at Least One Occasion	Number of Sites with Screen Submergence
<=10 ft.	185	61	
>10 ft. and <=20 ft.	507	73	
>20 ft. and <=30 ft.	611	59	
>30 ft. and <=45 ft.	278	33	
>45 ft. and <=60 ft.	128	15	
>60 ft.	42	1	
Total	1751	242	78

- Table 5.8 also summarizes the relative positions of the monitoring wells installed at the sites reviewed. For the purposes of this study, wells were classified as being "source zone", "up-gradient", "down-gradient", or "cross-gradient" depending on their position relative to the impacted soils "source zone" and the predominant groundwater flow direction at each site. Figure 5.5 schematically defines each of these categories.

Figure 5.5. Schematic Defining Well Location Categories Used in this Study.



It should be noted that a minimum of three appropriately positioned groundwater monitoring wells are needed to determine groundwater flow direction, and greater confidence in flow direction is usually achieved with more. Of the 270 sites in this study with one or more groundwater monitoring wells, only 190 sites (70%) had three or more monitoring wells and sufficient data to confidently determine a dominant flow direction; thus, the relative position to the source zone could be determined for only 1,462 of the 1,850 monitoring wells logged in the database for those 270 sites.

Based on those 1,462 monitoring wells, the percentage of monitoring wells classified as being in the source zone, or in the up-gradient, cross gradient, or down-gradient directions are 38%, 14%, 32%, and 16%, respectively. There were no down-gradient monitoring wells at 29% of these sites.

Table 5.8 a), b), and c). Summary of Spatial Distributions of Groundwater Monitoring Wells (MWs).

a) Distance to Furthest Monitoring Well From UST System Center or From Source Zone Center.

Criteria	Basis	Percentage of Sites Where the Distance to the Furthest MW is Less Than or Equal to 100 ft	Percentage of Sites Where the Distance to the Furthest MW is Less Than or Equal to 200 ft	Percentage of Sites Where the Distance to the Furthest MW is Less Than or Equal to 400 ft	Percentage of Sites Where the Distance to the Furthest MW is Less Than or Equal to 600 ft	Maximum Distance (ft)
Distance From UST System Center	264 sites with monitoring wells with identifiable UST system center locations	25%	50%	80%	89%	4,154
Distance From Source Zone Center	267 sites with monitoring wells	24%	53%	82%	91%	3,925

b) Number of Monitoring Wells In, Up-gradient, Down-gradient, or Cross-gradient of the Source Zone.

Criteria	Basis	Percentage of Sites Where the Number of MWs is Less Than or Equal to 0 wells	Percentage of Sites Where the Number of MWs is Less Than or Equal to 1 well	Percentage of Sites Where the Number of MWs is Less Than or Equal to 2 wells	Percentage of Sites Where the Number of MWs is Less Than or Equal to 3 wells	Maximum Number of Wells
Source Zone Monitoring Wells	190 sites 553 source zone wells	6%	37%	54%	74%	17
Up-gradient Monitoring Wells	190 sites 203 up-gradient wells	30%	73%	94%	98%	6
Down-gradient Monitoring Wells	190 sites 239 down-gradient wells	29%	65%	88%	94%	6
Cross-gradient Monitoring Wells	190 sites 467 cross-gradient wells	11%	36%	62%	77%	16
Total Number of Monitoring Wells	1,462 wells at 190 sites with 3+ monitoring wells, known* flow direction, and known* well position					

* known flow direction and well position at sites with sufficient data to confidently determine a dominant flow direction

c) Distance to Down-gradient Wells From Source Zone Center or Down-gradient Edge of Source Zone.

Criteria	Basis	Percentage of MWs Where the Distance is Less Than or Equal to 50 ft	Percentage of MWs Where the Distance is Less Than or Equal to 100 ft	Percentage of MWs Where the Distance is Less Than or Equal to 250 ft	Percentage of MWs Where the Distance is Less Than or Equal to 500 ft	Maximum Distance (ft)
Down-gradient of Source Zone Center	238 wells at 190 sites with 3+ monitoring wells and known* flow direction	12%	31%	68%	87%	3,454
Down-gradient of Source Zone Edge	237 wells at 190 sites with 3+ monitoring wells and known* flow direction	32%	53%	81%	92%	3,177

* known flow direction at sites with sufficient data to confidently determine a dominant flow direction

5.5 HYDROGEOLOGIC CONDITIONS AT THE LUST SITES REVIEWED

5.5.1 Subsurface Geologic Descriptors

The geology in Arizona is diverse, and is often described on the large-scale in terms of formal units (e.g. Moenkopi formation). On the LUST-site scale, geologic descriptions are less formal and more subjective and qualitative. Boring logs are the primary source of descriptive subsurface information for LUST sites, and these site-specific geologic interpretations can be as unique as the individuals logging them. For the purposes of this study, a set of standard qualitative geologic descriptors was established prior to file review, and the one most representative of the data from each site was selected. These descriptors are listed below in Table 5.9.

Table 5.9. Distribution of Saturated and Unsaturated Zone Geology for the Sites Reviewed.

Zone	Description	Geology	Frequency of Occurrence	Comment
Unsaturated based on 328 sites with known unsaturated zone geology	Unconsolidated Sediments	Interbedded Sands, Silts, Clays	182 (55%)	
		Mixed Sands, Silts, Clays	45 (14%)	
		Sands, Gravels, Cinders	88 (27%)	
		Silts, Clays	13 (4%)	
	Consolidated Materials	Coarse Grained Sedimentary	4 (1%)	33 of 328 sites show consolidated sediments in the unsaturated zone. However, no site shows exclusively consolidated sediments.
		Fine Grained Sedimentary	13 (4%)	
		Igneous, Metamorphic	8 (2%)	
		Limestone	1 (<1%)	
		Volcanic	7 (2%)	
Saturated based on 272 sites with known saturated zone geology	Unconsolidated Sediments	Interbedded Sands, Silts, Clays	126 (45%)	
		Mixed Sands, Silts, Clays	75 (27%)	
		Sands, Gravels, Cinders	52 (18%)	
		Silts, Clays	18 (6%)	
		None Encountered	11 (4%)	
	Consolidated Materials	Coarse Grained Sedimentary	4 (1%)	44 of 282 sites show consolidated sediments in the saturated zone. Only 11 sites show exclusively consolidated sediments.
		Fine Grained Sedimentary	18 (6%)	
		Igneous, Metamorphic	10 (4%)	
		Limestone	0 (0%)	
		Volcanic	12 (4%)	

For clarification, “mixed sands, silts, and clays” defines a mix of sands and silts and/or clays without noted structure or layering, as opposed to sediments that were primarily sands/gravels or silts/clays. The term “interbedded” refers to a distinct layering of more permeable and less permeable layers such as sands and gravels within less permeable layers such as silts and/or clays.

The relationship between qualitative site geology descriptors and Arizona Geologic Province is shown in Table 5.10. Unconsolidated sediments occur across all provinces, whereas consolidated sediments, when encountered, are predominantly found in the Transition and Colorado Plateau regions. Overall, the incidence of consolidated sediment encounters at the LUST sites studied was low.

Table 5.10. Occurrence of Qualitative Geologic Descriptors by Geologic Province.

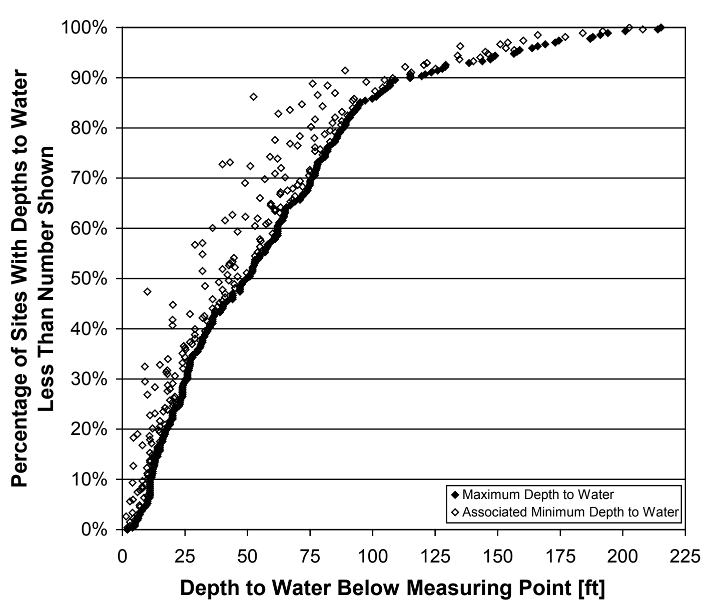
Zone	Description	Geology	Distribution as a Function of Geologic Province* BR (225 sites)	Tr (43 Sites)	CP (40 sites)	CO (25 sites)
Unsaturated Zone	Unconsolidated Sediments	None	0	0	0	0
		Interbedded Sands, Silts, Clays	65	11	7	5
		Mixed Sands, Silts, Clays	127	19	24	12
		Sands and Gravels	31	6	0	8
		Silts and Clays	2	4	7	0
		Unknown	2	2	3	0
	Consolidated Materials	None Encountered	215	27	29	24
		Unconsolidated Sediments and Bedrock	9	13	10	1
		Bedrock Only	0	0	0	0
		Unknown	3	2	2	0
Saturated Zone	Unconsolidated Sediments	None Encountered	4	4	3	0
		Interbedded Sands, Silts, Clays	36	7	5	4
		Mixed Sands, Silts, Clays	86	12	18	10
		Sands and Gravels	58	7	1	9
		Silts and Clays	7	4	6	1
		Unknown	36	8	8	1
	Consolidated Materials	None Encountered	176	15	20	23
		Unconsolidated Sediments and Bedrock	8	14	10	1
		Bedrock Only	4	4	3	0
		Unknown	39	9	8	1

* Geologic Provinces: BR-Basin and Range, Tr-Transition Zone, CP-Colorado Plateau, CO-Colorado River Valley

5.5.2 Depth-to-Groundwater

Figure 5.6 summarizes depth-to-groundwater (DTW) information extracted from the LUST files. The DTW is the distance to the water surface in a monitoring well, and this is typically measured from the top of the monitoring well casing. DTW is used here as an approximate measure of the depth-to-water below ground surface since the top-of-casing is typically not even with ground surface and the offset is rarely provided in reports. For each file reviewed, the data from one representative well were entered into the database; this included the maximum and minimum DTW

Figure 5.6. Depth-to-Groundwater for the LUST Sites Reviewed.



and any discernable temporal trends (i.e., rising, falling, seasonally fluctuating, no discernable trend). At about 50% of the sites the DTW was less than 50 ft, with almost 90 percent of the sites studied having a DTW of less than 100 ft. While not shown graphically, DTW showed no correlation with geologic province.

For sites with at least three years of groundwater elevation data, rising, falling, or seasonal water level trends were readily discernible for only 37 sites (14%).

5.5.3 Magnitude of Horizontal Hydraulic Gradient and Variability in Flow Direction

Horizontal hydraulic gradients and flow directions were determined from site-specific groundwater elevation maps. Groundwater flow directions for each site studied were assigned based on consideration of the groundwater elevation data and the spatial distribution of dissolved contaminants in groundwater. When time-series data were available, groundwater flow directions were determined for a range of times across the sampling duration.

Table 5.11 presents the results of this analysis for the 178 sites, including a breakdown by saturated zone geology. Since there were so few sites with only consolidated sediments in the saturated zone, these sites are listed together in this table.

Table 5.11 also summarizes hydraulic conductivity data; this table is a combination of values obtained from the file review (26 sites) and the supplemental data collection slug tests performed by ASU (11 sites). Very few aquifer characterization test results were available in the files because quantitative aquifer characterization is not a required site investigation component for LUST sites in Arizona.

Figure 5.7.
Range of Flow Direction Variability vs. Horizontal Hydraulic Gradient.

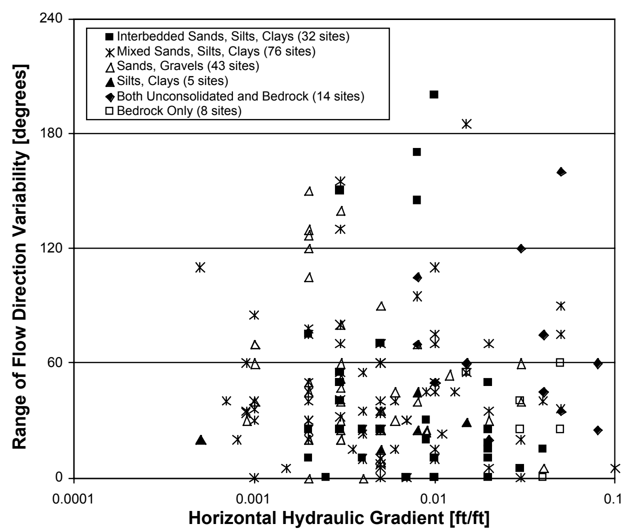


Figure 5.7 presents a plot of the range of flow directions determined for each site as a function of the horizontal hydraulic gradient at that site. It was suspected that the flow variability might be greater for smaller horizontal hydraulic gradients (because measurement errors are more significant), but the data did not support this hypothesis.

Table 5.11. Hydraulic Conductivity, Hydraulic Gradient, and Variability in Flow Direction.

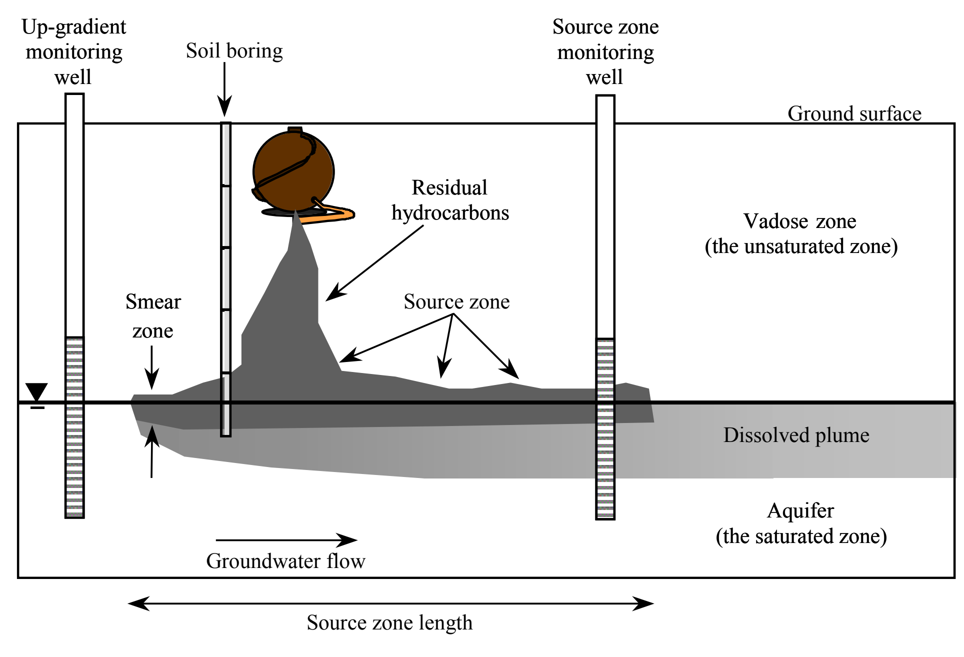
Saturated Zone Geology	Number of Sites	Distribution				
		Hydraulic Conductivity (K)(37 sites with hydraulic conductivity data)				
		Minimum K Value (ft/day)	Percentage of Sites With K Values Greater Than 0.1 ft/day	Percentage of Sites With K Values Greater Than 1 ft/day	Percentage of Sites With K Values Greater Than 10 ft/day	Maximum K Value (ft/day)
IB SSC[1]	4	0.029 ft/day	100%	100%	75%	79 ft/day
Mixed SSC[2]	15	0.006 ft/day	93%	80%	40%	139 ft/day
Sands, Gravels	8	0.051 ft/day	88%	88%	75%	129 ft/day
Silts, Clays	4	0.151 ft/day	100%	50%	25%	100 ft/day
Unconsolidated Sediments and Bedrock[3]	2	0.114 ft/day	100%	100%	0%	4.96 ft/day
Bedrock	4	0.03 ft/day	100%	75%	0%	5.08 ft/day
All Geology	37	0.006 ft/day	95%	81%	43%	139 ft/day
		Gradient (185 sites with data to determine flow direction and gradient)				
		Minimum Gradient (ft/ft)	Percentage of Sites With Gradients Greater Than 0.003 ft/ft	Percentage of Sites With Gradients Greater Than 0.006 ft/ft	Percentage of Sites With Gradients Greater Than 0.02 ft/ft	Maximum Gradient (ft/ft)
IB SSC[1]	31	0.002 ft/ft	68%	55%	6%	0.40 ft/ft
Mixed SSC[2]	78	0.0005 ft/ft	63%	36%	9%	0.10 ft/ft
Sands, Gravels	43	0.0009 ft/ft	42%	23%	7%	0.04 ft/ft
Silts, Clays	5	0.0005 ft/ft	80%	60%	0%	0.015 ft/ft
Unconsolidated Sediments and Bedrock[3]	19	0.0008 ft/ft	89%	84%	47%	0.40 ft/ft
Bedrock	9	0.015 ft/ft	100%	100%	78%	0.14 ft/ft
All Geology	185	0.0005 ft/ft	64%	45%	15%	0.40 ft/ft
		Range of Flow Direction Variability (degrees) (193 sites with data to determine range of flow direction variability)				
		Minimum Range (degrees)	Percentage of Sites With a Range Greater Than 20°	Percentage of Sites With a Range Greater Than 45°	Percentage of Sites With a Range Greater Than 90°	Maximum Range (degrees)
IB SSC[1]	33	0°	58%	33%	15%	360°
Mixed SSC[2]	84	0°	74%	36%	10%	360°
Sands, Gravels	47	0°	83%	45%	19%	360°
Silts, Clays	5	15°	60%	0%	0%	45°
Unconsolidated Sediments and Bedrock[3]	16	20°	94%	69%	25%	160°
Bedrock	8	0°	75%	38%	0%	60°
All geology	193	0°	75%	39%	13%	360°

1 - IB SSC – Interbedded Sands, Silts, Clays
2 - Mixed SSC – Mixed Sands, Silts, Clays
3 - Includes all geologies where bedrock was encountered beneath unconsolidated sediments, regardless of type.

5.6 CHARACTERIZATION OF GROUNDWATER IMPACTS AT LUST SITES

A simplistic conceptual model of the subsurface beneath a leaking underground storage tank (LUST) site is shown in Figure 5.8. Gasoline leaking from the tank, lines, or dispenser system flows down through the vadose (or "unsaturated") zone under the influence of gravity. If the gasoline spill is sufficiently large, the gasoline liquid reaches groundwater, and then spreads laterally (because it is less dense than water). With time, a "smear zone" of gasoline-impacted soils is created by the natural rising and falling of the groundwater. Depending on the history of the rising and falling, at any given time the smear zone may be in partial contact with groundwater, it may be submerged by groundwater, or it may not even be in direct contact with groundwater. Larger spills result in the creation of lenses of gasoline both above and below the water table. These lenses are created by displacing varying amounts of groundwater from pore space that was previously saturated or very nearly saturated with water. Wherever gasoline contacts water, petroleum constituents will dissolve into the groundwater and will then move with the groundwater flow. Even with smaller spills, chemicals can leach down to groundwater or be transported as vapors to groundwater.

Figure 5.8. Simplistic LUST Site Conceptual Model.



As discussed previously, the extent and magnitude of hydrocarbon impacts to soils and groundwater beneath LUST sites is most often assessed in Arizona by drilling soil borings and installing groundwater monitoring wells. In this section, data for contaminant concentrations in soil and groundwater collected during the file review and supplemental data collection are summarized.

5.6.1 Source Zone Size

In the context of the discussions that follow, the "source zone" is the region of the subsurface where one finds petroleum liquids in the soil pores (e.g., the smear zone in Figure 5.8). It is sonamed because it is the origin of groundwater impacts (either by direct contact with groundwater or via leaching and vapor transport). Many federal and state regulatory programs focus on characterization and treatment of source zones, as experience suggests that groundwater contamination often dissipates if the source is successfully treated.

For each LUST file reviewed, a source zone was defined in two-dimensions on a plan view map. The boundaries of each source zone were selected largely based on professional judgment after considering:

- the soil boring logs (in particular, any indication of stains and odors in soils),
- groundwater sample data (any dissolved BTEX concentrations in excess of 1000 ug/L), and
- soil concentration data (any benzene and/or TPH soil concentrations equal to or greater than 0.1 mg/kg or 100 mg/kg, respectively).

The quantity and quality of data available for source zone definition varied from site to site. While most of the 324 facilities represented in the database were single source zone facilities, 13 (4% of the facilities) had multiple source zones. Four (4) of these source zones had little data associated with them or fell within the plume of a more dominant source zone. As a result, these were not recorded as independent sites. Nine (9) of the facilities, however, had independent multiple source zones (eight with two source zones and one with four source zones).

Once the source zone boundaries were assigned for each site, the source zone size was characterized by *length* in the dominant direction of groundwater flow and *width* perpendicular to the length. The source zone area was computed using an equation for the area of an ellipse with the length of the principle axes equal to the estimated length and width.

Results of this analysis are summarized below in Table 5.12, where they are presented as a function of saturated and unsaturated zone geology descriptors, depth-to-groundwater, whether or not free-product was detected at the site, and free-product thickness. Each is discussed below. In brief, about 50% of the sites had source zones sizing ranging from 1000 – 10,000 ft^2. Only 14% of sites had source zones smaller than 1000 ft^2 and 4% of sites had source zones larger than 100,000 ft^2.

5.6.1.1 Effect of Geology on Source Zone Size

Table 5.12 suggests that the source zone size distributions were similar for most classes of the qualitative geologic descriptors. The only exception appears to be that class of sites having a vadose zone geology qualitatively described to be “silts, clays”; this class of sites has fewer large source zones (>10,000 ft^2) than the other classes of sites.

Table 5.12. Source Zone Size as a Function of Geology, Presence of Free-Product, Free-Product Thickness, and Depth-to-Water.

Criteria		Number of Sites	Minimum Source Zone Size [ft²]	Percentage of Sites With Source Zone Areas Greater Than 1,000 ft²	Percentage of Sites With Source Zone Areas Greater Than 10,000 ft²	Percentage of Sites With Source Zone Areas Greater Than 100,000 ft²	Maximum Source Zone Size [ft²]
Unsaturated Zone Geology	IB SSC[1]	64	188	86%	25%	3.13%	244,851
	Mixed SSC[2]	132	104	87%	31%	3.0%	217,305
	Sands, Gravels	33	153	82%	36%	3.0%	126,671
	Silts, Clays	7	345	86%	29%	0.0%	31,649
	Unconsolidated and Bedrock[3]	26	79	85%	58%	15%	201,804
	Bedrock only	0	---	---	---	---	---
	All sites where unsaturated zone geology is known	262	79	86%	33%	4.2%	244,851
Saturated Zone Geology	IB SSC[1]	43	188	88%	26%	4.7%	244,851
	Mixed SSC[2]	101	188	87%	33%	4.0%	217,305
	Sands, Gravels	67	104	81%	34%	1.5%	126,671
	Silts, Clays	10	226	80%	10%	0.0%	12,745
	Unconsolidated and Bedrock[3]	29	201	93%	48%	14%	201,804
	Bedrock only	10	79	80%	40%	0.0%	28,390
	All sites where saturated zone geology is known	260	79	86%	33%	4.2%	244,851
Depth to Water (ft below measuring pt)	<=25	78	79	87%	35%	5.1%	201,804
	25< x <=50	53	194	91%	40%	7.5%	244,851
	50< x <=75	52	153	25%	25%	3.8%	217,305
	75< x <=100	43	104	81%	33%	0.0%	96,261
	>100	38	283	91%	32%	2.6%	158,256
	All sites where depth-to-water is known	264	79	86%	33%	4.2%	244,851
Presence of Free Product	FP Not Present	136	79	77%	17%	0.0%	45,668
	FP Present	103	408	96%	56%	11%	244,851
	All sites where presence of FP is known	239	79	85%	34%	4.6%	244,851
Free Product Thickness (ft)	<=0.25	33	408	88%	33%	3.0%	122,966
	0.25< x <=1.0	25	1528	100%	60%	8.0%	201,804
	1.0< x <=2.0	18	1628	100%	72%	22%	244,851
	>2.0	25	1002	100%	72%	16%	199,935
	All sites where FP thickness is known	101	408	96%	56%	11%	244,851

1. IB SSC – Interbedded Sands, Silts, Clays
2. Mixed SSC – Mixed Sands, Silts, Clays
3. Includes all geologies with both unconsolidated sediments and bedrock

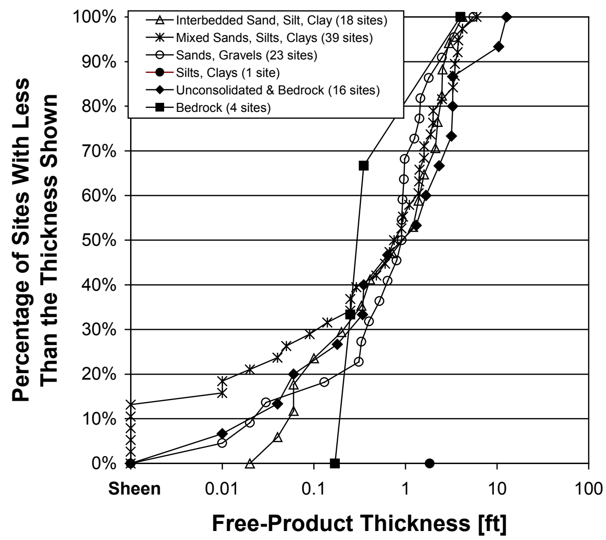
5.6.1.2 Effect of Depth-to-Groundwater on Source Zone Size

While it might be expected that impacts would be less extensive at deep groundwater sites (>50 ft to groundwater), Table 5.12 suggests that the distribution of source zone sizes is similar for all depth-to-groundwater groupings examined. This implies that the LUST releases at the sites reviewed were often large enough to reach groundwater. This is further supported by the frequency of free-product detections at the LUST sites reviewed as discussed below in §5.6.1.3.

5.6.1.3 Free-Product Presence and Free-Product Thickness vs. Source Zone Size

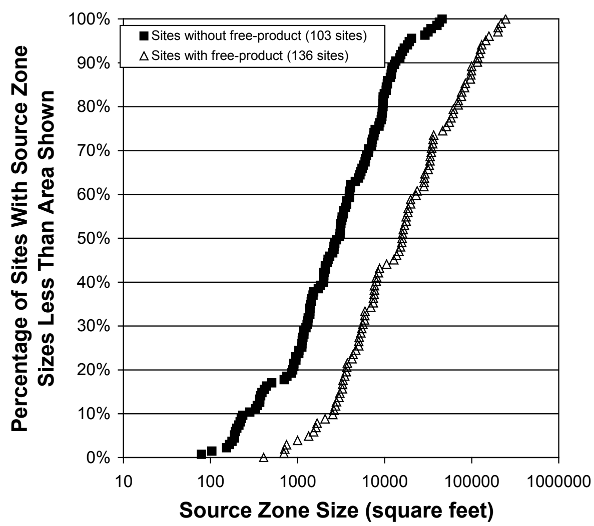
Free-product (mobile liquid gasoline) was detected in one or more groundwater monitoring wells at 101 of the sites reviewed. The distribution of free-product thicknesses is shown in Figure 5.9. For approximately 50% of the free-product sites, the maximum measured free-product thickness was less than one foot. The maximum reported free-product thickness was 12.6 ft for all files reviewed.

Figure 5.9. Free-Product Thickness vs. Saturated Zone Geology Descriptor.



There was an apparent correlation between source zone size and the presence of free-product at LUST sites; on average, source zone sizes were roughly eight times larger at sites having measurable free-product in one or more wells than at sites without free product accumulation in wells (Figure 5.10).

Figure 5.10. Source Zone Size Distributions.



While the presence of free-product seemed to be related to source zone size, the source zone size did not appear to be significantly affected by free-product thickness. In other words, the extent of impact was not necessarily larger at sites with larger measurable free-product thicknesses, and therefore, the data suggested that free-product thickness was not a good indicator of source zone size.

It was also noted that the distribution of reported free-product thicknesses was similar across all qualitative saturated zone geologic descriptors, as shown in Figure 5.9.

5.6.2 Occurrence of Chemicals Dissolved in Groundwater in LUST Source Zones

Dissolved concentration data from source zone groundwater monitoring wells were summarized below in terms of the number of sites with useful data for each chemical and the distribution of chemical concentrations observed in the LUST files reviewed in this study. As discussed previously, target chemicals were selected for this study based on regulatory interest in Arizona, regulatory interest nationwide, and consideration of gasoline composition and chemical properties.

5.6.2.1 Occurrence Based on Data Obtained from the File Review

Table 5.13 summarizes the concentration data compiled during the LUST file review. In that exercise, one or two source zone monitoring wells were selected, and the dissolved concentrations for all chemicals of interest were recorded. The State of Arizona has not historically required the monitoring or reporting of some of these chemicals, and as a result, data were not available for many of the sites. When available, there often had to be retrieved from the original laboratory data sheets. *Because of this, it is important to note that the number of sites having reported concentrations does not necessarily reflect the frequency of occurrence of these chemicals across all LUST sites. These tables simply summarize the range of concentrations observed at the sites for which data were available, and should only be interpreted as such.*

Table 5.13 (a) and (b). Data Availability and Groundwater Concentrations for Chemicals Found in Source Zones [all data from file review].

(a) Sites with Gasoline and Other Contaminants (237 sites with 1+ source zone well and gasoline impact)

Chemical[1]	AZ Water Quality Standard (ug/L)	Number of Sites with Detectable Groundwater Concentrations[2]	Concentration in Groundwater (ug/L)			
			25% of Sites Have Concentrations Less Than:	50% of Sites Have Concentrations Less Than:	75% of Sites Have Concentrations Less Than:	Maximum Concentration
Benzene	5	226	573	3,850	13,000	130,000
Toluene	1,000	226	400	5,500	22,000	80,000
Ethylbenzene	700	229	180	1,400	3,200	52,000
Total Xylenes	10,000	231	990	6,600	17,000	150,000
Methyl tert-Butyl Ether	20[3]	109	58	660	5,400	100,000
1,2,4-Trimethylbenzene	---	155	71	470	1,200	29,000
1,3,5-Trimethylbenzene	---	142	43	220	583	7,300
Naphthalene	---	123	30	160	580	16,000
n-Propylbenzene	---	119	26	81	210	2,100
Isopropylbenzene	---	96	9	37	73	760
n-Butylbenzene	---	75	9.6	51	105	3,800

(b) Sites with no Gasoline Contamination (13 sites with 1+ source zone well and no gasoline impact)

Chemical[1]	AZ Water Quality Standard (ug/L)	Number of Sites with Detectable Groundwater Concentrations[2]	Concentration in Groundwater (ug/L)			
			25% of Sites Have Concentrations Less Than:	50% of Sites Have Concentrations Less Than:	75% of Sites Have Concentrations Less Than:	Maximum Concentration
Benzene	5	11	4.6	69	435	10,000
Toluene	1,000	10	4.6	31	3,525	21,000
Ethylbenzene	700	11	11.0	29	845	27,000
Total Xylenes	10,000	11	11.3	91	6,265	100,000
Methyl tert-Butyl Ether	20[3]	1	7.1	7.1	7.1	7.1
1,2,4-Trimethylbenzene	---	7	4.6	91	2,050	3,800
1,3,5-Trimethylbenzene	---	7	5.3	24	450	8,300
Naphthalene	---	8	31	66	535	720
n-Propylbenzene	---	5	4.4	80	250	370
Isopropylbenzene	---	5	5.0	50	59	140
n-Butylbenzene	---	5	7.3	20	76	170

1. Data for BTEX constituents and MTBE obtained from the individual well records, the remaining analytes from the 8260 record.
2. Table is based only on detectable concentration data for the constituents listed. There should be no inferences to non-detectable concentrations nor the lack of analytical data for constituents.
3. The reporting level, and the remedial level in the case that MTBE potentially affects a drinking water well

The data are summarized in terms of the range of concentrations as well as the distribution of dissolved concentrations (as expressed by quartiles). For example, for sites reporting detectable concentrations, benzene and MTBE concentrations were reported to be greater than 3,400 ug/L and greater than 620 ug/L, respectively, at 50% of the sites. The data showed roughly 1,000 ug/L or greater concentrations of many of these chemicals (i.e., BTEX, MTBE, trimethyl-benzenes) in source zone groundwater at a significant fraction of the sites with usable data.

When comparing the results presented in Table 5.13 (or the following tables 5.15 and 5.17) with results contained in the California and Texas LUST study reports, it is important to recognize that the California BTEX study report presents the site-, time-, and spatially averaged groundwater concentrations, while Table 5.13 presents single sample data from source zone monitoring wells. Thus the reported California concentrations distributions would be expected to be lower than the results in Table 5.13. For example, in the California study reports that 50% of sites had benzene concentrations less than 22.7 ug/L, while Table 5.13 suggests that 50% of sites had source zone concentrations less than 3400 ug/L.

5.6.2.2 Occurrence Based on Data Obtained from Supplemental Groundwater Sample Collection and Analysis by GC/FID-PID

Because the LUST file review provided little data on some of the chemicals of interest, groundwater samples were collected from 50 LUST sites and then analyzed at ASU by gas chromatography (GC) using flame-ionization (FID) and photo-ionization (PID) detectors. Consulting firms collected these groundwater samples during their routine quarterly monitoring of these sites. Details of the chemical analysis method are contained in Appendix B.

A total of 452 groundwater samples from 50 LUST sites in 25 Arizona cities were analyzed. Of the 50 LUST sites, 42 were classified as "gasoline-contaminated" sites based on available site and release-history data. From those 42 gasoline-contaminated sites, 137 of the groundwater samples were from source zone wells. The geographic distribution of the 50 LUST sites is summarized in terms of the cities/towns in Table 5.14.

Table 5.14. Number of LUST Sites per City From Which Supplemental Groundwater Samples were Collected for GC/FID&PID Analysis.

City	Number of Sites
Holbrook	10
Phoenix	9
Yuma	3
Tucson	3
Winslow	2
Nogales	2
Mesa	2
Bullhead City	2
Willcox	1
Tempe	1
Star Valley	1
Somerton	1
Snowflake	1
Scottsdale	1
Safford	1
Prescott	1
Pinetop	1
Glendale	1
Gilbert	1
Fountain Hills	1
Eagar	1
Douglas	1
Chandler	1
Casa Grande	1
Avondale	1
Total	50

The frequency of detection above reportable[9] concentrations of the target chemicals is summarized in Table 5.15 in terms of sites, and wells. This summary is limited to data from the sites having gasoline releases (data from all sites is found in Appendix B). MTBE was the most frequently detected compound – 89% of the samples contained MTBE above a reportable concentration. The mono-aromatic compounds (benzene, toluene, xylenes, ethylbenzene, trimethylbenzene) were detected in 60 to 85% of the source zone well samples. Naphthalene, DIPE, and ETBE were detected less frequently – in about 30 – 50% of the samples, and all other chemicals (mostly the alcohols) were detected in less than 11% of the samples. Compared with the results using data from the ADEQ LUST file review (Table 5.13), BTEX compounds were detected more frequently at lower concentrations. For toluene and ethylbenzene, the maximum concentrations were relatively consistent with the database data (within the same order of magnitude); however, 25%, 50%, and 75% percentiles were one order of magnitude lower. MTBE concentrations were also slightly lower; however, the maximum concentration was about the same. The concentration distributions of trimethylbenzenes and naphthalene seemed to be roughly consistent with the LUST file database results.

TBA concentrations were quantified but are not reported here, because it was suspected that there was co-elution of other gasoline-related chemicals with TBA[10].

Table 5.15. Chemical Detection and Groundwater Concentration Distributions for Gasoline-Contaminated Sites [supplemental sample collection and GC-FID/PID analysis].

Chemical	Number of Occurrences and Frequency of Detection						Concentration in Groundwater (ug/L)				
	Sites (33 sites)		Wells (89 wells)		Samples (137 samples)		25% of Sites Have Groundwater Concentrations Less Than:	50% of Sites Have Groundwater Concentrations Less Than:	75% of Sites Have Groundwater Concentrations Less Than:	Maximum Concentration	Detectable Concentration
	Number	Frequency	Number	Frequency	Number	Frequency					
Methanol	5	15%	15	17%	15	11%	6,700	7,500	63,000	380,000	5,000
Ethanol	2	6%	8	9%	8	6%	5,400	6,700	8,900	15,000	5,000
Isopropanol	0	0%	3	3%	3	2%	5,800	6,300	6,500	6,600	5,000
n-Propanol	3	9%	0	0%	0	0%	---	---	---	---	5,000
n-Butanol	9	27%	5	6%	5	4%	26,000	28,000	34,000	34,000	10,000
MTBE	21	64%	81	91%	122	89%	43	210	780	110,000	1.0
DIPE	18	55%	49	55%	66	48%	17	110	420	3,100	1.0
ETBE	28	85%	41	46%	48	35%	11	80	260	15,000	1.0
Benzene	26	79%	77	87%	115	84%	65	420	2,900	59,000	0.5
Toluene	26	79%	68	76%	103	75%	11	86	810	90,000	0.5
Ethylbenzene	25	76%	64	72%	96	70%	54	310	840	21,000	0.5
M/p-Xylene	25	76%	64	72%	97	71%	37	350	1,200	44,000	0.5
o-Xylene	26	79%	61	69%	94	69%	19	130	680	33,000	0.5
1,3,5-TMB	27	82%	61	69%	90	66%	23	210	770	7,200	1.0
1,2,4-TMB	26	79%	67	75%	99	72%	30	320	1,800	11,000	1.0
1,2,3-TMB	15	45%	56	63%	82	60%	15	230	630	2,600	1.0
Naphthalene	33	100%	36	40%	44	32%	160	330	1,300	17,000	100

[9] - in the context of this part of the study a "reportable" chemical concentration is one that was quantified with confidence; chemicals may have been detected but not quantified due to interferences with other closely-eluting chemicals giving higher detector responses.

[10] - Rhodes, I.A.L. and A.W. Verstuyft. 2001. Selecting Analytical Methods for the Determination of Oxygenates in Environmental Samples and Gasoline. *Environmental Testing & Analysis,* March/April 2001, The Target Group. Available at http://www.api.org

5.6.2.3 Occurrence Based on Data Obtained from Supplemental Groundwater Sample Collection and Analysis by GC-MS

It was discovered in the course of that work that the GC-FID-PID headspace analysis was not useful for quantifying TBA (due to suspected co-elution problems in field samples), and the detection levels for methanol, ethanol, and other alcohols were several orders of magnitude greater than the detection levels of other compounds. Thus, use of a heated purge-and-trap/gas chromatography/mass spectrometry (P&T/GC-MS) was explored. GC-MS analysis offers the potential to better identify and quantify a wider range of chemicals, by adding another dimension to the analysis. In addition to retention time and detector response, MS spectra can be compared with a library of mass spectra to provide a more positive identification of specific chemicals. Heated P&T pre-concentration of samples also offers lower detection levels than headspace analysis for chemicals with low Henry's constants. Details of the analysis are contained in Appendix B.

Table 5.16. Supplemental Groundwater GC/MS Analysis Site Distribution by City.

City	Number of Sites
Holbrook	11
Tucson	3
Douglas	2
Phoenix	2
Prescott	2
Rimrock	2
Willcox	2
Yuma	2
Arivaca	1
Benson	1
Buckeye	1
Clifton	1
Eagar	1
Fountain Hills	1
Safford	1
Snowflake	1
Springerville	1
Williams	1
Total	36

In this phase of the study, supplemental groundwater samples were collected from a total of 252 wells at 36 LUST sites. The site distribution by Arizona cities/towns is shown in Table 5.16. The sites were selected based primarily on ease of access and on information obtained during the ADEQ file review (i.e., gasoline-impacted sites with detectable concentrations were desirable).

Table 5.17 presents the detection frequency of gasoline constituents in source zone wells at these sites and the distribution of concentrations. Relative to the results presented above, the frequency of occurrence and concentration distributions are similar for the mono-aromatics and MTBE (detected most frequently) and for the alcohols (infrequent detections). The most significant differences are for ETBE and DIPE, which are detected less frequently in this data set, and naphthalene, which was detected more frequently in this data set. The former might be explained by co-elution in the GC/FID/PID analysis and the latter could be explained by the increased resolution and detection limits of the GC-MS analysis.

5.6.2.4 MTBE Detections in Groundwater Across Arizona

Analytical data for MTBE was available for only 181 of 274 sites with groundwater quality data. While MTBE was not detected at all sites, its occurrence was relatively widespread across the state. The following are cities with sites where MTBE concentrations in groundwater were detected in excess of 20 ug/L:

- Arivaca
- Avondale
- Bisbee
- Black Canyon City
- Cottonwood
- Dewey
- Douglas
- Duncan
- Goodyear
- Holbrook
- Kingman
- Lake Havasu City
- Phoenix
- Prescott
- Rimrock
- Rock Springs
- Springerville
- Tempe
- Thatcher
- Tucson

- Buckeye
- Bullhead City
- Casa Grande
- Chandler
- Christopher Creek
- Coolidge
- Cordes Junction
- Eagar
- Ehrenberg
- Flagstaff
- Fountain Hills
- Fredonia
- Gila Bend
- Globe
- Littlefield
- Mohave Valley
- Munds Park
- Page
- Parker
- Payson
- Petrified Forest
- Safford
- St. Johns
- Scottsdale
- Sedona
- Show Low
- Somerton
- South Tucson
- Wellton
- Wickenburg
- Willcox
- Williams
- Winslow
- Yuma

Table 5.17. Chemical Detection and Groundwater Concentration Distributions in Source Zones at Gasoline Contaminated Sites [supplemental sample collection and GC-MS analysis].

Chemical	Number of Occurrences and Frequency of Detection				Concentration in Groundwater (ug/L)				
	Site (30 sites)		Wells (141 wells)		25% of Sites Have Groundwater Concentrations Less Than:	50% of Sites Have Groundwater Concentrations Less Than:	75% of Sites Have Groundwater Concentrations Less Than:	Maximum Concentration	Detectable Concentration
	Number	Frequency	Number	Frequency					
Methanol	0	0%	0	0%	---	---	---	---	500
Ethanol	1	3%	1	1%	670	670	670	670	100
Isopropanol	1	3%	1	1%	1,100	1,100	1,100	1,100	100
n-Propanol	2	7%	2	1%	630	640	660	670	50
n-Butanol	7	23%	11	8%	250	1,000	6,100	9,600	50
MTBE	25	83%	100	71%	91	330	3,800	68,000	1
TBA	15	50%	36	26%	110	620	2,100	20,000	50
DIPE	6	20%	13	9%	22	58	610	1,500	1
ETBE	2	7%	2	1%	16	31	46	61	1
Benzene	30	100%	137	97%	160	1,500	8,600	120,000	0.5
Toluene	30	100%	131	93%	29	310	6,500	110,000	0.5
Ethylbenzene	29	97%	127	90%	76	1,100	3,700	96,000	0.5
M/p-Xylene	30	100%	135	96%	52	1,100	4,900	73,000	0.5
o-Xylene	29	97%	124	88%	29	440	4,400	98,000	0.5
1,3,5-TMB	30	100%	131	93%	12	470	1,300	27,000	0.5
1,2,4-TMB	30	100%	130	92%	65	1,400	3,500	170,000	0.5
1,2,3-TMB	30	100%	129	91%	22	470	1,000	58,000	0.5
Naphthalene	30	100%	131	93%	28	320	1,100	63,000	0.5

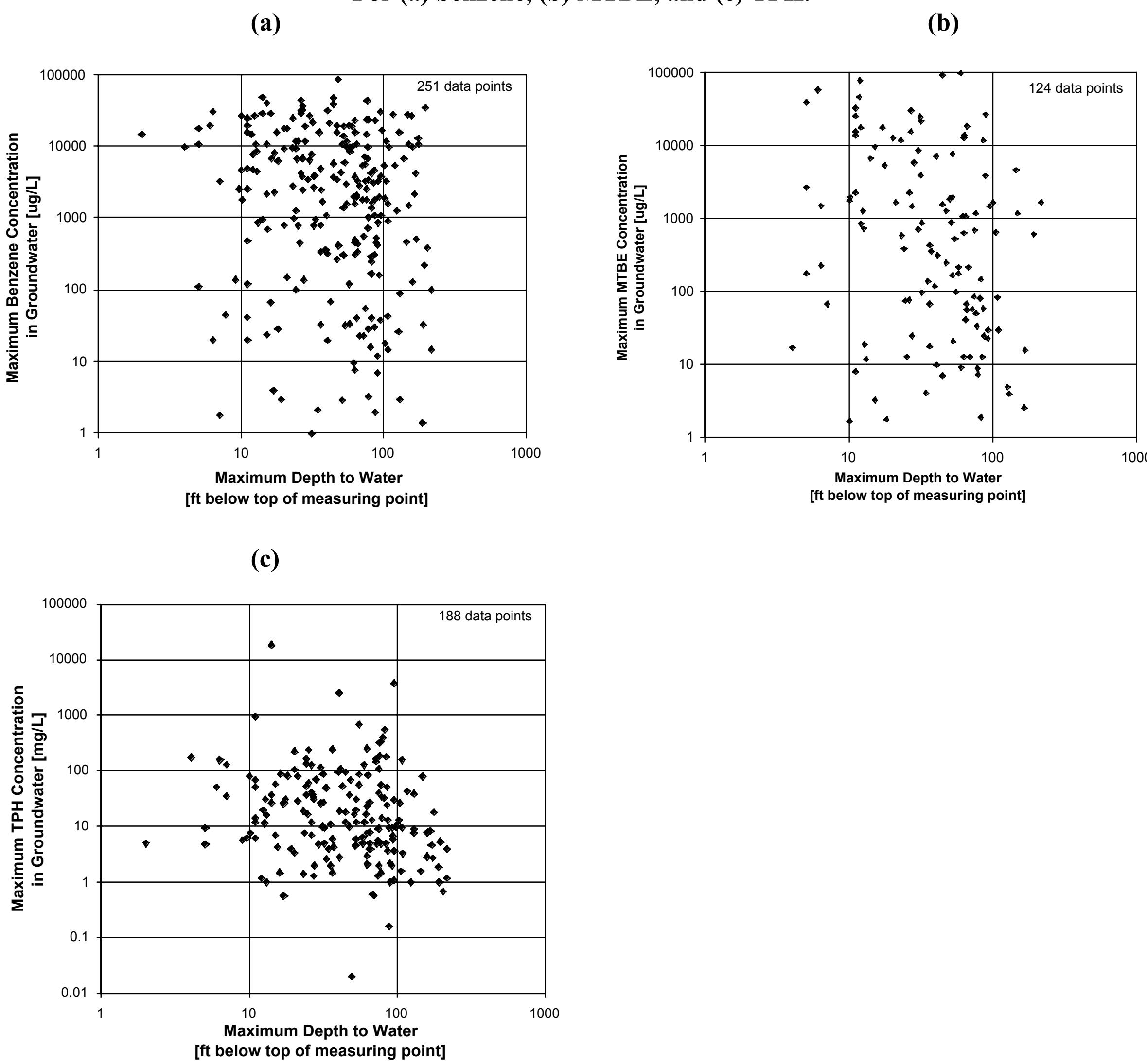
5.6.3 Groundwater Impacts Versus Depth

Data from the LUST file review database were used to examine relationships between groundwater impacts and distances between groundwater and: a) ground surface, and b) the deepest depth of penetration into the soil as measured by chemical-specific and total petroleum hydrocarbon (TPH) concentrations in soil concentrations. In this analysis, the maximum source zone groundwater concentration at each site along with soil concentration information from all borings at each site was used.

5.6.3.1 Groundwater Impacts Versus Depth-to-Groundwater from Ground Surface

The dissolved contaminant concentration versus depth-to-groundwater analysis is presented in Figures 5.11a - c. The data in these figures exhibit little dependence of depth-to-groundwater on the dissolved groundwater concentration distributions. This is consistent with the observation that source zone size does not appear to be significantly affected by depth-to-groundwater.

Figure 5.11.
Maximum Contaminant Concentration vs. Maximum Depth-to-Water
For (a) benzene, (b) MTBE, and (c) TPH.

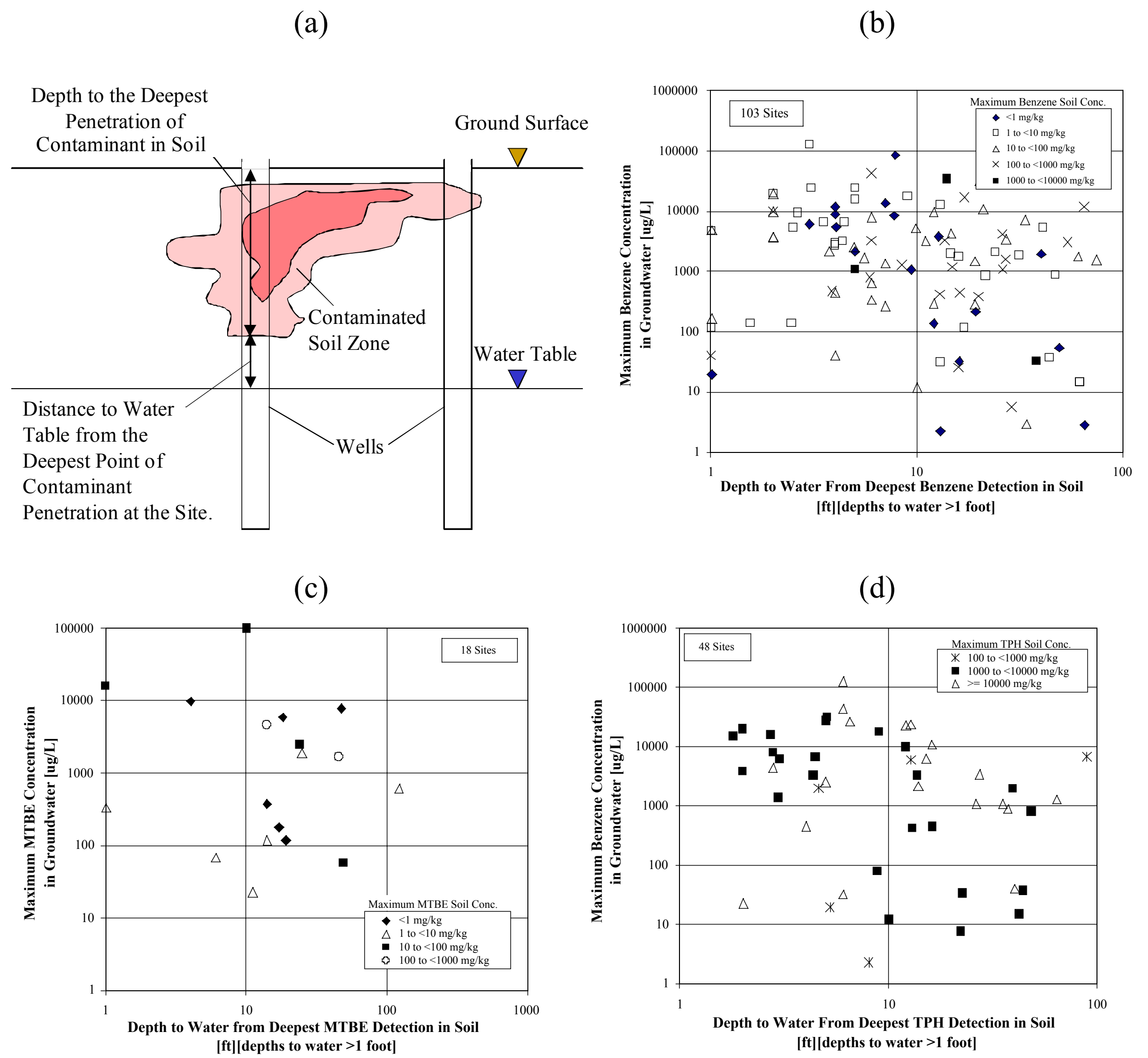


5.6.3.2 Groundwater Impacts Versus Distance Between Groundwater and Vadose Zone Impacted Soil

In Arizona (and other states), decisions concerning soil clean-up levels and the need to investigate groundwater impacts may be linked to the distance between groundwater and the deepest measured soil impacts (pictured in Figure 5.12a). For example, if in the course of a soils investigation impacted soils are only observed to a depth of 20 ft below ground surface and groundwater is known to be encountered at 200 ft below ground surface, then one might decide not to sample soils down to groundwater, or even to sample groundwater at all. Data from the LUST file review were used to examine the relationship between source zone groundwater concentrations and the distance between groundwater and the deepest observed soil impacts.

Figures 5.12b - 5.12d plot maximum source zone groundwater concentrations vs. distance (from the deepest depth of detection in soil to groundwater) for benzene, MTBE, and total petroleum hydrocarbons (TPH). Given the practical resolution of depths to groundwater and depths of soil sample collection, distances less than 1 ft were considered to be in contact with groundwater and were not plotted on these graphs. To help assess the effect of soil concentration on the results, data points were segregated by the maximum soil concentration detected at each site. As can be seen, there is no clear trend in this data. The implication is that the combination of distance between deepest measured vadose zone soil impacts and groundwater, and maximum measured soil concentration is not a reliable predictor of groundwater impacts.

Figure 5.12.
Maximum Groundwater Concentrations for Select Constituents vs. Depth-to-Water from Deepest Detection in Soil for benzene, MTBE, and TPH:(a) Schematic of Distance Between Depth of Deepest Vadose Zone Penetration and Groundwater (as indicated by soil concentration data); (b) benzene; (c) MTBE; (d) TPH.



5.6.4 Groundwater Impacts Versus Geology Descriptor

The relationship between contaminant concentrations in groundwater and the qualitative vadose zone geology descriptor was examined. Based on the results presented in Table 5.18, it was concluded that the source zone groundwater concentration distributions did not vary significantly between the different vadose zone geology descriptors.

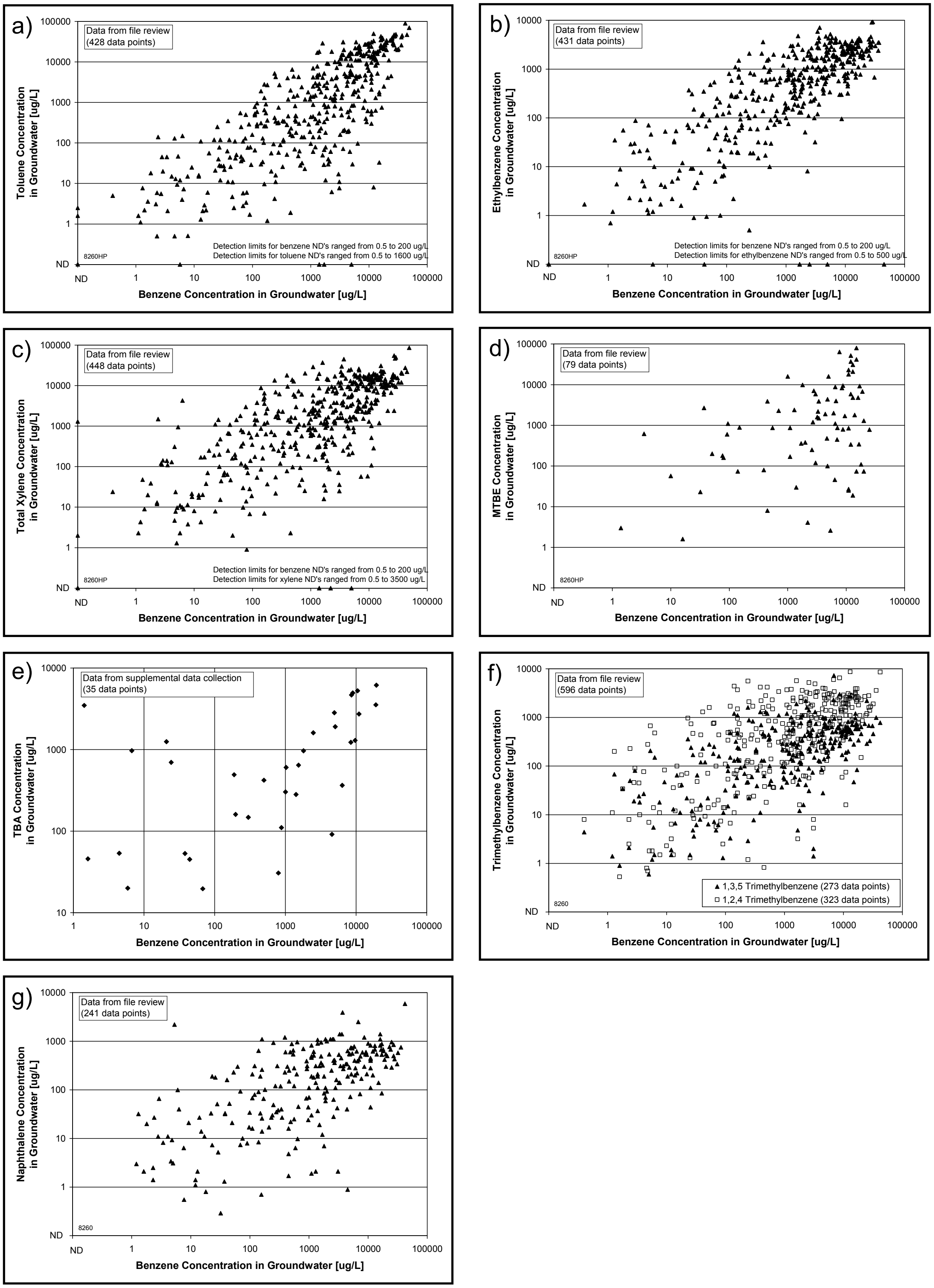
Table 5.18. Source Zone Groundwater Concentration Distributions for Selected Chemicals by Vadose Zone Geology Descriptor.

Chemicals	Vadose Zone Geologic Descriptor	Number of Sites	Concentration in Groundwater (ug/L) 25% of Sites Have Groundwater Concentrations Less Than:	50% of Sites Have Groundwater Concentrations Less Than:	75% of Sites Have Groundwater Concentrations Less Than:	Maximum Concentration
Benzene	Interbedded Sands, Silts, Clays	56	110	2,000	10,000	41,000
	Mixed Sands, Silts, Clays	128	1,100	4,500	15,000	130,000
	Sands, Gravels	32	860	2,000	13,000	49,000
	Silts, Clays	10	2,200	4,800	11,000	31,000
	Unknown	2	8,300	17,000	25,000	33,000
Toluene	Interbedded Sands, Silts, Clays	55	86	1,500	16,000	80,000
	Mixed Sands, Silts, Clays	128	61	5,900	22,000	90,000
	Sands, Gravels	32	1,100	5,000	20,000	70,000
	Silts, Clays	10	950	17,000	25,000	44,000
	Unknown	2	12,000	24,000	35,000	47,000
1,2,4 TMB	Interbedded Sands, Silts, Clays	37	45	400	1,900	4,000
	Mixed Sands, Silts, Clays	92	200	760	2,300	8,700
	Sands, Gravels	25	320	1,500	2,800	140,000
	Silts, Clays	7	1,500	2,100	2,700	6,000
	Unknown	1	140	140	140	140
MTBE	Interbedded Sands, Silts, Clays	27	22	360	3,800	100,000
	Mixed Sands, Silts, Clays	66	50	500	3,900	52,000
	Sands, Gravels	19	24	140	2,500	40,000
	Silts, Clays	4	210	590	750	1,500
	Unknown	1	1,500	1,500	1,500	1,500

5.6.5 Co-occurrence of Chemicals in LUST Source Zones

The co-occurrence of chemicals and relationships between their concentrations in source zone groundwater was examined. Figure 5.13 summarizes the results in a series of plots where target chemical concentrations are plotted vs. benzene groundwater concentration for the same sample. Benzene was selected simply because it has been a regulatory target analyte for many years (similar plots are presented in the California LUST study report). Figure 5.13 contains a selection of the co-occurrence plots presented in Appendix B for different data sources (e.g., LUST file review, supplemental samples with GC-MS analysis), and the data source is noted in each plot.

Figure 5.13. Co-occurrence of Chemicals with Benzene in Source Zone Groundwater.



5.6.6 Measured Groundwater Impacts vs. Measured Concentrations in Soil

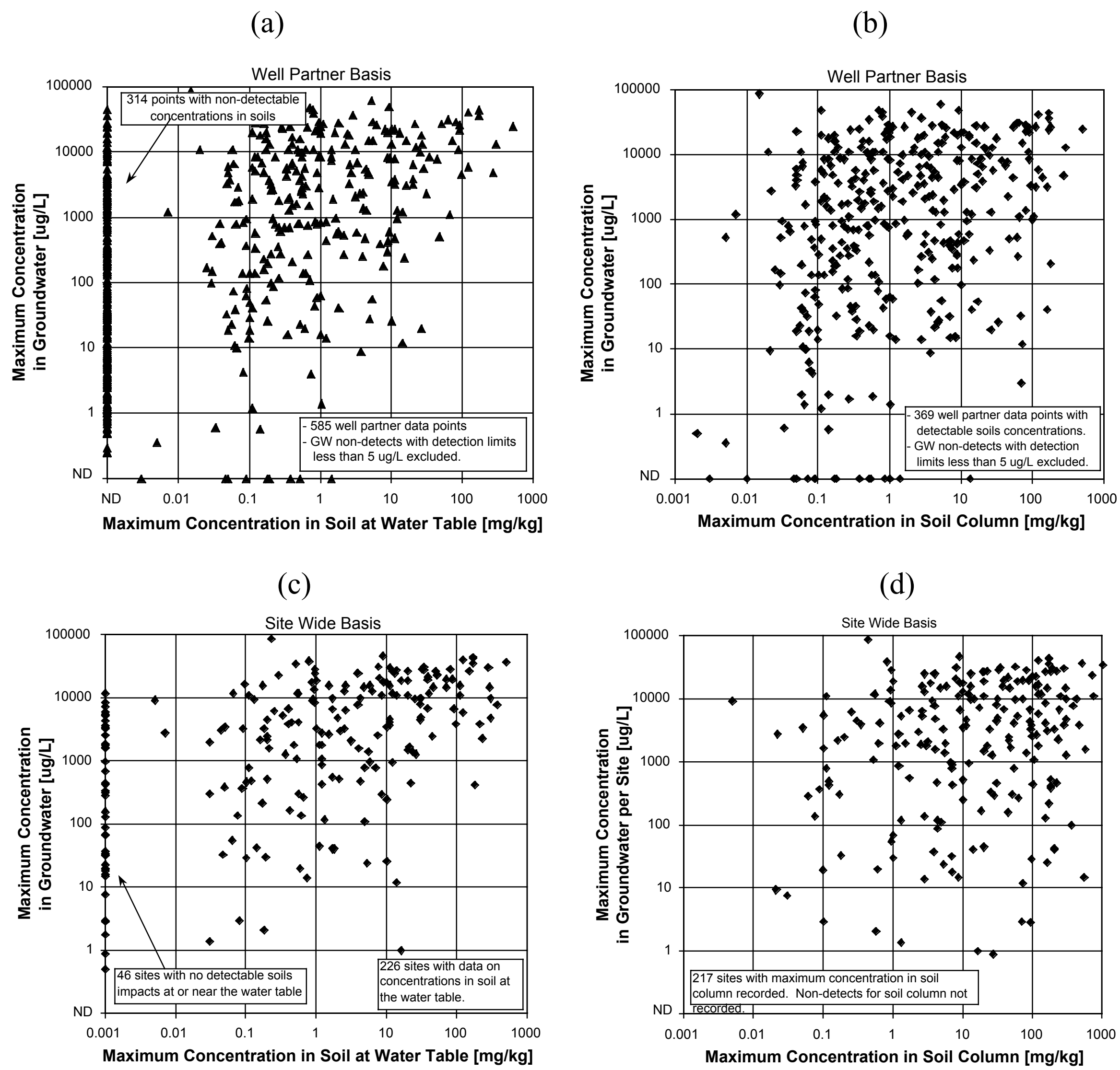
Regulatory programs often develop target soil cleanup concentrations based on linear partitioning relations and chemical transport equations. Typically these relations assume that increasing soil concentrations correspond to increasing groundwater concentrations. In addition, it is assumed that measured soil concentrations are reliable indicators of dissolved groundwater concentrations. Data from LUST file review database were used to explore the relationship between soils and groundwater concentrations. To do this, maximum groundwater concentrations for each site were compared to maximum detectable soil concentrations for each site in the following four ways:

<table>
<tr><td>1)</td><td>Maximum Groundwater Concentration</td><td>vs.</td><td>Maximum Soil Concentration Anywhere in Soil Column</td><td rowspan="2">Site-Wide
Maximum concentrations for a site</td></tr>
<tr><td>2)</td><td>Maximum Groundwater Concentration</td><td>vs.</td><td>Maximum Soil Concentration at Groundwater</td></tr>
<tr><td>3)</td><td>Maximum Groundwater Concentration</td><td>vs.</td><td>Maximum Soil Concentration Anywhere in Soil Column</td><td rowspan="2">Well-Soil Boring Partners
Soil boring and monitoring well within approximately 10 ft of each other</td></tr>
<tr><td>4)</td><td>Maximum Groundwater Concentration</td><td>vs.</td><td>Maximum Soil Concentration at Groundwater</td></tr>
</table>

Sample results from this analysis are presented in Figure 5.14, where benzene groundwater concentrations are plotted vs. maximum benzene concentrations in soils at groundwater. As can be seen, soil concentration is not a reliable indicator of groundwater concentration. Soils concentrations ranging from non-detect to almost 500 mg/kg showed corresponding groundwater concentrations ranging from 1 to 87,000 ug/L. Even more compelling is the observation that 314 of 411 (76%) boreholes that showed non-detectable benzene soils concentrations had detectable groundwater concentrations ranging from 0.5 to 45,000 ug/L, 233 (57%) of which were above the Arizona water quality standard of 5 ug/L for benzene.

TPH concentration data also indicated no correlation for the methods described above. Soils concentrations ranging from non-detect to over 10,000 mg/kg showed corresponding groundwater concentrations ranging from 1 mg/L to over 1,000 mg/L. In addition, of the 297 boreholes with non-detectable TPH concentrations in the soil, 191 boreholes (64%) had detectable contaminant concentrations in groundwater, 25% of which were above 5 mg/L and ranged to over 1,000 mg/L.

Figure 5.14.
Benzene Concentrations in GW vs. Benzene Concentrations in Soil:
(a) Maximum Concentration in GW and the Maximum Concentration in Soil at the Water Table Using Well-Soil Boring Partners; (b) Maximum Concentration in GW and the Maximum Concentration in Soil in the Soil Column Using Well-Soil Boring Partners; (c) Maximum Concentration in GW and Maximum Concentration in Soil at the Water Table on a Site-Wide Basis; and (d) Maximum Concentration in GW and Maximum Concentration in Soil in the Soil Column on a Site-Wide Basis. Data Acquired Using the LUST File Review Database.



5.6.7 Spatial Extent of Groundwater Impacts

As discussed above, the California and Texas LUST studies reduced the groundwater concentration data for each site to a single parameter – a plume length, or distance down-gradient to a target dissolved concentration.

Upon review of the characteristics of this data set, and in particular the spatial distribution of groundwater monitoring wells at Arizona LUST sites, it was decided that a plume-length analysis was inappropriate for this data set.

Instead, the data from all sites were composited and reduced to the concentration distribution format presented in Tables 5.19 and 5.20. These tables present the number of times chemical concentrations exceed order-of-magnitude concentrations (10, 100, 1000 ug/L) for given categories of distance away from: a) the down-gradient edge of the source zone, and b) the UST system center. The results are presented for benzene, toluene, xylenes, and MTBE, and the number of wells falling into each distance category are listed. Of importance is the fact that the density of wells is highest within a distance of 100 ft and it becomes much less dense for distances greater than 200 ft. Also of importance are the variations in flow direction noted previously, and the impact that this has on selecting locations for down-gradient wells.

Despite these limitations in the data set, some observations were made. For example:

- Source zone level dissolved concentrations (1,000 ug/L) were rarely detected at distances more than about 500 ft away from the UST system center.

- The data suggested that MTBE impacts are likely to extend greater distances down-gradient than BTEX impacts to groundwater.

- Dissolved plume extent were less likely to correlate with distances down-gradient from UST system centers than distance from down-gradient edges of source zones.

Table 5.19. Groundwater Concentration vs. Down-gradient Distance From Source Zone Edge.

Down-gradient Distance From Source Zone Edge[1]	Number of Sites With Wells in Distance Range	Number of Wells in Distance Range for Which Lab Data is Available	Distribution: Number of Wells for Distance Range (Percentage of Wells for Distance Range) for Which the Concentration in Groundwater Exceeded the Value Shown[2]			Maximum Concentration for Range
			Benzene Concentration in Groundwater			
			10 ug/L	100 ug/L	1,000 ug/L	Maximum
0-100 ft	98	134	65 (49%)	39 (29%)	3 (2%)	2,900 ug/L
101-200 ft	47	52	15 (29%)	5 (10%)	2 (4%)	1,300 ug/L
201-300 ft	24	28	10 (36%)	4 (14%)	0 (0%)	430 ug/L
301-400 ft	8	9	3 (33%)	1 (11%)	0 (0%)	500 ug/L
401-600 ft	8	10	2 (20%)	1 (10%)	0 (0%)	190 ug/L
601-800 ft	8	8	3 (38%)	0 (0%)	0 (0%)	45 ug/L
801-1,000 ft	3	5	2 (40%)	0 (0%)	0 (0%)	29 ug/L
> 1,000 ft	3	3	0 (0%)	0 (0%)	0 (0%)	1 ug/L
			Toluene Concentration in Groundwater			
			10 ug/L	100 ug/L	1,000 ug/L	Maximum
0-100 ft	98	132	41 (31%)	16 (12%)	1 (1%)	1,400 ug/L
101-200 ft	47	51	7 (14%)	3 (6%)	0 (0%)	1,000 ug/L
201-300 ft	24	27	4 (15%)	1 (4%)	0 (0%)	170 ug/L
301-400 ft	8	9	2 (22%)	0 (0%)	0 (0%)	15 ug/L
401-600 ft	8	10	1 (10%)	0 (0%)	0 (0%)	12 ug/L
601-800 ft	8	8	0 (0%)	0 (0%)	0 (0%)	6 ug/L
801-1,000 ft	3	5	0 (0%)	0 (0%)	0 (0%)	6 ug/L
> 1,000 ft	3	3	0 (0%)	0 (0%)	0 (0%)	2 ug/L
			Xylene Concentration in Groundwater			
			10 ug/L	100 ug/L	1,000 ug/L	Maximum
0-100 ft	98	129	66 (51%)	34 (26%)	6 (5%)	4,000 ug/L
101-200 ft	47	47	13 (28%)	6 (13%)	1 (2%)	2,800 ug/L
201-300 ft	24	26	7 (27%)	3 (12%)	1 (4%)	1,800 ug/L
301-400 ft	8	8	1 (13%)	0 (0%)	0 (0%)	14 ug/L
401-600 ft	8	6	1 (17%)	1 (17%)	0 (0%)	247 ug/L
601-800 ft	8	7	1 (14%)	0 (0%)	0 (0%)	74 ug/L
801-1,000 ft	3	3	3 (100%)	0 (0%)	0 (0%)	98 ug/L
> 1,000 ft	3	3	0 (0%)	0 (0%)	0 (0%)	3 ug/L
			MTBE Concentration in Groundwater			
			10 ug/L	100 ug/L	1,000 ug/L	Maximum
0-100 ft	98	57	25 (44%)	13 (23%)	2 (4%)	25,000 ug/L
101-200 ft	47	29	8 (28%)	3 (10%)	1 (3%)	14,000 ug/L
201-300 ft	24	10	6 (60%)	2 (20%)	1 (10%)	1,100 ug/L
301-400 ft	8	4	1 (25%)	1 (25%)	0 (0%)	570ug/L
401-600 ft	8	6	3 (50%)	1 (17%)	0 (0%)	360 ug/L
601-800 ft	8	3	2 (67%)	1 (33%)	0 (0%)	110 ug/L
801-1,000 ft	3	3	1 (33%)	1 (33%)	0 (0%)	160 ug/L
> 1,000 ft	3	2	1 (50%)	0 (0%)	0 (0%)	21 ug/L

1. Wells down-gradient of down-gradient source zone edge and distance parallel to plume axis
2. Non-detects greater than 5 ug/L (mg/L for TPH) are excluded

Table 5.20. Groundwater Concentration vs. Down-gradient Distance From UST System Center.

Down-gradient Distance From UST System Center[1]	Number of Sites With Wells in Distance Range	Number of Wells in Distance Range for Which Lab Data is Available	Distribution: Number of Wells for Distance Range (Percentage of Wells for Distance Range) for Which the Concentration in Groundwater Exceeded the Value Shown[2]			Distribution: Maximum Concentration for Range
			Benzene Concentration in Groundwater			
			10 ug/L	100 ug/L	1,000 ug/L	Maximum
0-100 ft	98	360	297 (83%)	255 (71%)	170 (47%)	47,000 ug/L
101-200 ft	47	113	71 (63%)	55 (49%)	35 (31%)	49,000 ug/L
201-300 ft	24	61	34 (56%)	29 (48%)	27 (44%)	28,000 ug/L
301-400 ft	8	48	27 (56%)	19 (40%)	10 (21%)	18,000 ug/L
401-600 ft	8	22	10 (45%)	8 (36%)	3 (14%)	27,000 ug/L
601-800 ft	8	9	4 (44%)	2 (22%)	1 (11%)	1,100 ug/L
801-1,000 ft	3	6	2 (33%)	0 (0%)	0 (0%)	28 ug/L
> 1,000 ft	3	12	3 (25%)	0 (0%)	0 (0%)	45 ug/L
			Toluene Concentration in Groundwater			
			10 ug/L	100 ug/L	1,000 ug/L	Maximum
0-100 ft	98	357	278 (78%)	223 (62%)	159 (45%)	80,000 ug/L
101-200 ft	47	112	54 (48%)	42 (38%)	28 (25%)	70,000 ug/L
201-300 ft	24	60	31 (52%)	26 (43%)	19 (32%)	54,100 ug/L
301-400 ft	8	46	16 (35%)	12 (26%)	9 (20%)	22,000 ug/L
401-600 ft	8	21	7 (33%)	5 (24%)	4 (19%)	46,000 ug/L
601-800 ft	8	9	2 (22%)	1 (11%)	0 (0%)	1,000 ug/L
801-1,000 ft	3	6	0 (0%)	0 (0%)	0 (0%)	6 ug/L
> 1,000 ft	3	12	0 (0%)	0 (0%)	0 (0%)	6 ug/L
			Xylene Concentration in Groundwater			
			10 ug/L	100 ug/L	1,000 ug/L	Maximum
0-100 ft	98	356	301 (85%)	263 (74%)	196 (55%)	80,000 ug/L
101-200 ft	47	110	64 (58%)	51 (46%)	33 (30%)	86,000 ug/L
201-300 ft	24	58	34 (59%)	29 (50%)	22 (38%)	58,000 ug/L
301-400 ft	8	45	23 (51%)	17 (38%)	12 (27%)	18,000 ug/L
401-600 ft	8	18	9 (50%)	7 (39%)	5 (28%)	23,600 ug/L
601-800 ft	8	8	3 (38%)	2 (25%)	1 (13%)	2,800 ug/L
801-1,000 ft	3	5	1 (20%)	0 (0%)	0 (0%)	74 ug/L
> 1,000 ft	3	9	3 (33%)	0 (0%)	0 (0%)	98 ug/L
			MTBE Concentration in Groundwater			
			10 ug/L	100 ug/L	1,000 ug/L	Maximum
0-100 ft	98	134	90 (67%)	60 (45%)	28 (21%)	100,000 ug/L
101-200 ft	47	44	24 (55%)	17 (39%)	6 (14%)	80,000 ug/L
201-300 ft	24	25	16 (64%)	9 (36%)	8 (32%)	31,000 ug/L
301-400 ft	8	19	10 (53%)	7 (37%)	3 (16%)	14,000 ug/L
401-600 ft	8	12	6 (50%)	3 (25%)	1 (8%)	1,300 ug/L
601-800 ft	8	3	0 (0%)	0 (0%)	0 (0%)	5 ug/L
801-1,000 ft	3	3	1 (33%)	0 (0%)	0 (0%)	44 ug/L
> 1,000 ft	3	7	3 (43%)	2 (29%)	0 (0%)	160 ug/L

1. Wells down-gradient of UST system center and distance parallel to plume axis
2. Non-detects greater than 5 ug/L (mg/L for TPH) are excluded

5.6.8 Trends in Groundwater Concentrations and Depths to Groundwater

In performing the ADEQ LUST file review, reviewers noted the presence and absence of obvious temporal trends in depth-to-groundwater and dissolved groundwater concentrations. This determination was subjective and based on visual review of data. Table 5.21 briefly summarizes the information captured during the LUST file review process. There was no obvious trend in water levels or concentrations for most of the LUST files reviewed. Furthermore, most obvious concentration trends did not readily correlate with rising or falling groundwater levels.

Table 5.21. Water Level and Groundwater Concentration Trends.

Trend for Water Level (WL) and/or Groundwater Concentration (GW Conc.)	**Distribution - Number of Sites With Discernible Water Level and/or Pre-remediation Groundwater Concentration Trends**	
	Sites with long-term water level trends (270 sites with at least one monitor well)	
	Number of Sites	The fluctuation at any given site fell within the following range
Rising WL	7	8 to 25 feet
Falling WL	18	1 to 27 feet
Seasonal WL fluctuation	12	3 to 20 feet
No WL trend	233	---
	Sites with at least one well with long-term pre-remediation groundwater concentration trends	
	Benzene (268 sites)	MTBE (181 sites)
Rising GW Conc.	2	2
Falling GW Conc.	46	3
No GW Conc. trend	222	176
	Sites with at least one well with long-term pre-remediation groundwater concentration trends and long-term water level trends	
	Benzene (268 sites)	MTBE (181 sites)
Rising WL and Falling GW Conc.	3	0
Rising WL and Rising GW Conc.	0	0
Falling WL and Falling GW Conc.	5	0
Falling WL and Rising GW Conc.	0	0
Rising/Falling WL and No GW Conc. trend	17	16
Rising/Falling GW Conc. and No WL trend	35	5

5.6.9 Supplemental Data Collection – GW Impacts at Six Sites

Six sites were chosen for additional characterization work with the hope that the data from these sites could be presented as being representative of the larger population of LUST sites. Activities at these sites generally focused on the installation of temporary groundwater sampling points and a one-time collection and analysis of groundwater samples from those points as well as all existing groundwater monitoring wells.

Sites selected for this phase of the supplemental characterization activities were chosen because it was judged that they were reasonably well characterized relative to the general population of

LUST sites (i.e., both spatial and temporal characterization of groundwater impacts). In addition, the six sites were selected based on consideration of:

- accessibility (cooperative owners/operators, responsible parties, surrounding property owners, and municipalities),
- horizontal hydraulic gradient (relatively steep and flat gradient sites were desired, as well as variable gradient direction sites),
- availability of historical groundwater MTBE concentration data,
- qualitative geologic descriptors for the saturated zones at the six sites relative to the spectrum of conditions across Arizona, and
- sites with depth-to-water less than 40 feet (to minimize investigational cost – results from the file review suggest that groundwater impacts are relatively insensitive to depth-to-groundwater).

Characteristics of sites selected for the field work are summarized in Table 5.22. Existing groundwater wells were sampled at each site and samples were analyzed at ASU by the GC-MS method discussed in Appendix B. These data, and the historical information available from the ADEQ LUST file review, were then used to develop a site-specific supplemental characterization strategy.

The general plan included the following: a) development of a site-specific sampling plan based on available data and pre-characterization sample collection and analysis, b) collection of one continuous core to verify the site geology suggested by existing boring logs, c) installation of temporary sampling wells, d) collection of groundwater samples from all pre-existing and temporary wells, e) on-site analysis of groundwater samples by GC-FID, f) revision of the sampling plan based on the results of (e), g) off-site analysis of groundwater samples by GC-MS, and h) survey of all sampling locations. Groundwater samples were analyzed for the same suite of target analytes previously used for the supplemental groundwater analysis program.

Supplemental site characterization field work began in mid-October 2002 and ended in late-December 2002. The site-specific activities are summarized in Table 5.22. As is typical of LUST site investigations, sampling locations were limited by physical constraints (i.e., buildings, utility conduits, etc.) and off-site property access agreements.

Site plan view maps showing existing wells, temporary wells, and other relevant features are provided in Appendix C, along with tabular summaries of the groundwater concentration data. Table 5.23 briefly summarizes some of the results and observations.

Table 5.22. Site Characteristics Based on Historical and Pre-Characterization Sampling.

ADEQ Facility ID	Vadose Zone Geologic Descriptor --- Saturated Zone Geologic Descriptor	Depth to GW [ft]	Horizontal Hydraulic Gradient --- Flow Direction Variability [degrees]	Source Zone Wells	Up-gradient Wells	Cross-gradient Wells	Down-gradient Wells	Benzene Source Conc. [ug/L]	MTBE Source Conc. [ug/L]	Extent of Dissolved Impacts Suggested by Pre-Characterization and Historical Data
2072	Mixed Sands, Silts, Clays --- Mixed Sands, Silts, Clays	41	0.01 --- 75^o	8	1	16	5	11,000	394	Disseminated impact within 300' of release. MTBE detects 300+ feet from the source.
1301	Mixed Sands, Silts, Clays --- Mixed Sands, Silts, Clays	30	0.002 --- 50^o	1	1	4	0	5,083	7,288	Impact limited to source zone area – no indication of contaminant migration.
1254	Mixed Sands, Silts, Clays --- Interbedded Sands, Silts, Clays	17	0.02 --- 25^o	6	0	8	3	1,568	242	Impact limited to source zone area – no indication of contaminant migration.
1224	Mixed Sands, Silts, Clays --- Interbedded Sands, Silts, Clays	26	0.01 --- 200^o	8	2-Unknown[1]			476	2,909	Low level impacts noted within 100' of source zone. No significant contaminant migration. Seasonally variable flow direction.
1329	Mixed Sands, Silts, Clays --- Mixed Sands, Silts, Clays	11	< 0.001 --- Unknown	2	4-Unknown[2]			5.6	6,439	Localized heavy impact – no indication of contaminant migration.
1491	Mixed Sands, Silts, Clays --- Mixed Sands, Silts, Clays	11	< 0.001 --- Unknown	2	6-Unknown[2]			7,802	7,296	Predominantly MTBE impact isolated to source zone area – no indication of contaminant migration.

1. Unknown well position since flow direction was listed as unknown because of seasonal variability
2. Unknown well position since flow direction was listed as unknown because of very flat gradients

Table 5.23. Brief Summary of Supplemental Field Characterization Activities.

ADEQ Facility ID	Number of Borings	Total Feet Drilled	Type of Drilling	# GW Samples Collected from Borings	# GW Samples From Monitor Wells	Total # of GW Samples Collected	Relevant Field Comments
2072	7	322	Auger	7	16	23	Continuous core not possible - Split spoon sampling on 1 foot intervals near water table.
1301	15	527	GeoProbe	15	10	25	Continuous core collected in 1 borehole.
1254	9	272	Auger	9	13	22	Continuous core not possible - Split spoon sampling on 1 foot intervals near water table.
1224	7	234	Auger	11	10	21	Continuous core collected in 1 borehole. Vertical groundwater sample investigations attempted/performed at 3 locations.
1329	15	362	GeoProbe	26	6	32	Continuous cores collected in 2 boreholes. Vertical groundwater sample investigations performed at 7 sample locations.
1491	24	376	GeoProbe	28	10	38	Continuous core collected in 1 borehole. Vertical groundwater sample investigations performed at 4 sample locations.

Table 5.24. Brief Summary of Supplemental Site Characterization Results.

	Facility 2072	Facility 1301	Facility 1254	Facility 1224	Facility 1329	Facility 1491
Chemical	Chemicals Present in Source Zone?					
Methanol	---	---	---	---	---	---
Ethanol	---	---	---	---	---	---
Isopropanol	---	---	---	---	---	---
MTBE	Yes	Yes	Yes	Yes	Yes	Yes
TBA	Yes	Yes	Yes	Yes	Yes	Yes
DIPE	---	---	---	---	---	---
ETBE	---	---	---	---	---	---
n-Propanol	---	---	---	---	---	---
Benzene	Yes	Yes	Yes	Yes	Yes	Yes
n-Butanol	---	---	---	---	Yes	---
Toluene	Yes	Yes	Yes	Yes	Yes	Yes
Ethylbenzene	Yes	Yes	Yes	Yes	Yes	---
Xylenes	Yes	Yes	Yes	Yes	Yes	---
TMB’s	Yes	Yes	Yes	Yes	Yes	Yes
Naphthalene	Yes	Yes	Yes	Yes	Yes	Yes
Chemical	Chemicals Present Down-Gradient?					
Methanol	---	---	---	---	---	---
Ethanol	---	---	---	---	---	---
Isopropanol	---	---	---	---	---	---
MTBE	---	Yes	Yes	Yes	Yes	Yes
TBA	Yes	Yes	Yes	Yes	Yes	---
DIPE	---	---	---	---	---	---
ETBE	---	---	---	---	---	---
n-Propanol	---	---	---	---	---	---
Benzene	Yes	Yes	Yes	Yes	---	---
n-Butanol	Yes	---	---	---	Yes	---
Toluene	Yes	Yes	Yes	Yes	---	---
Ethylbenzene	Yes	Yes	Yes	Yes	---	---
Xylenes	Yes	Yes	Yes	Yes	---	---
TMB’s	Yes	Yes	Yes	Yes	---	---
Naphthalene	Yes	Yes	Yes	Yes	Yes	---
Criteria	Extent of Dissolved Contaminants					
Max. Distance from UST System Center that Chemicals of Interest Were Detected	850 ft	450 ft	550 ft	125 ft	90 - 290 ft	375 ft
Chemicals Present at that Maximum Distance	BTEX TMB’s Naphthalene	MTBE	BE MTBE TBA	MTBE TBA	MTBE TBA	MTBE
Assessment of Down-gradient Extent of Contamination in Groundwater	> 850 ft	> 450 ft	> 550 ft	> 125 ft	90 - 290 ft	> 375 ft
Comments	See Table 5.24 - Continuation					

Table 5.24 - Continued. Brief Summary of Supplemental Site Characterization Results.

Comments – Extent of Dissolved Contamination
Facility 2072 - Plume running southeast with free-product at 300 ft from UST system and benzene concentrations of 3403 ug/L present at 500 ft. Contamination within 250 ft of UST system appears to be broadly disseminated. Unable to track main axis of plume beyond 550 ft of UST system due to utility clearance; however, monitoring wells show benzene extending to at least 850 ft (246 ug/L).
Facility 1301 - Contaminant concentrations found along northeastern border of property over 100 ft from UST system (2,220 ug/L benzene and 2,150 ug/L MTBE) - Access prevented full delineation of source zone area. Low MTBE concentrations (6 – 17 ug/L) detected up to 450 ft in the northeasterly direction. Possible 2nd unrelated source of contamination detected at 500 ft east of site based on strong odors from groundwater samples. Drilling permit restricted further investigation of this source zone.
Facility 1254 - Plume extending over 550 ft from UST system. Heavy impact noted at 250 ft (2,200 ug/L benzene, 370 ug/L MTBE) with diminishing concentrations at 550 ft (260 ug/L benzene, 298 ug/L MTBE). It appears that there is little to no attenuation of MTBE between the source and 550 ft down-gradient. Unable to track plume further due to budget and time constraints.
Facility 1224 - Down-gradient direction is not well defined for site. Impacts observed at 125 ft from the UST system (86 ug/L MTBE), including MTBE to SW. Unrelated 2nd source also discovered within 120 ft of UST system and could be responsible for impacts noted in facility MWs in that direction. Signature of contaminant in that area suggests very weathered product.
Facility 1329 - MTBE detected at 184 ug/L 90 ft to the south of the UST system. 143 ug/L TBA and low levels of n-butanol, naphthalene, and MTBE were detected at 290 ft to the southwest. Unable to track contaminant due to access and utility clearance.
Facility 1491 - Concentrations exceeding 1,000 ug/L extend over 150 ft from the UST System in south and southwesterly directions. MTBE detections extend to the south and southwest up to 375 ft. Attempts to track main axis of plume constrained by access. Investigations 700 ft from UST system showed no detectable concentrations, although investigations were not in a direct line with more proximal impacts.

6.0 ASSESSMENT OF GROUNDWATER ELEVATION MEASUREMENT ERRORS

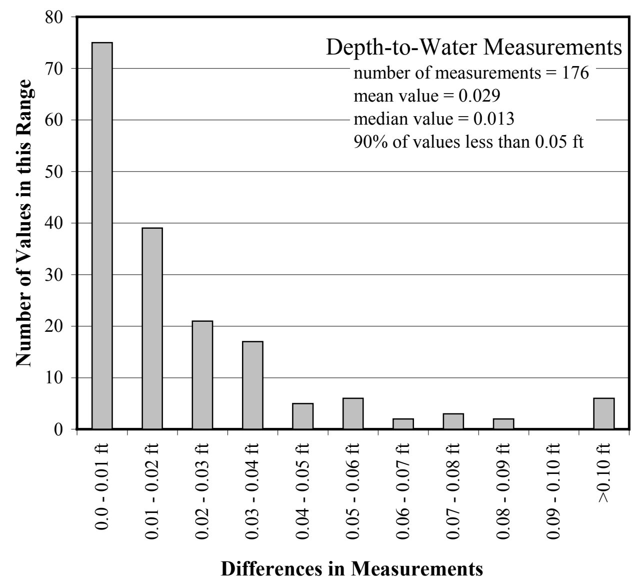
The determination of groundwater flow direction is a critical step in any LUST site characterization as it influences the placement of groundwater monitoring wells and the interpretation of groundwater concentration data. Groundwater flow direction is generally determined by a sequence of events involving: a) the measurement of depth-to-groundwater relative to the top-of-well-casing for groundwater monitoring wells at a site, b) the survey of the well locations and top-of-casing elevations, c) computation of the water table elevation at each well (top-of-casing elevation – depth-to-groundwater), d) creating water table elevation contour lines, and e) determination of the magnitude and direction of the hydraulic gradient across the site (generally assumed to be perpendicular to groundwater table elevation contour lines).

Given that the spatial dimensions of many LUST site monitoring well networks are on the order of 100 ft, and that hydraulic gradients typically fall in the range 0.001 – 0.010 ft/ft, it can be shown that errors in groundwater table elevation determination are significant when they approach the 0.1 – 1 ft range. Thus, a study was initiated to assess the magnitude of errors induced by typical field measurement practices. The methods and results are presented briefly below.

6.1 ASSESSMENT OF DEPTH-TO-WATER MEASUREMENT ERRORS

Depth-to-water measurements were made at six sites by groups of two or three people using two different water level detectors. Summaries of the results are presented in Figures 6.1 and 6.2. Figure 6.1 summarizes the differences in depth-to-water measurements made by different individuals using the same water level detector, while Figure 6.2 summarizes the differences in depth-to-water at each well for the two different water level detectors when used by the same individual. In both cases, the magnitude, or absolute difference, between measurements is being presented

Figure 6.1. Measurement Differences Between Individuals on the Same Well Using the Same Water-Level Indicators.



The results in Figure 6.1 show that the average measurement difference between individuals using the same device is about 0.03 ft, and that 90% of all measurement differences were <0.05 ft.

Figure 6.2. Differences Between Water Level Measurements at the Same Well Using Different Water-Level Indicators.

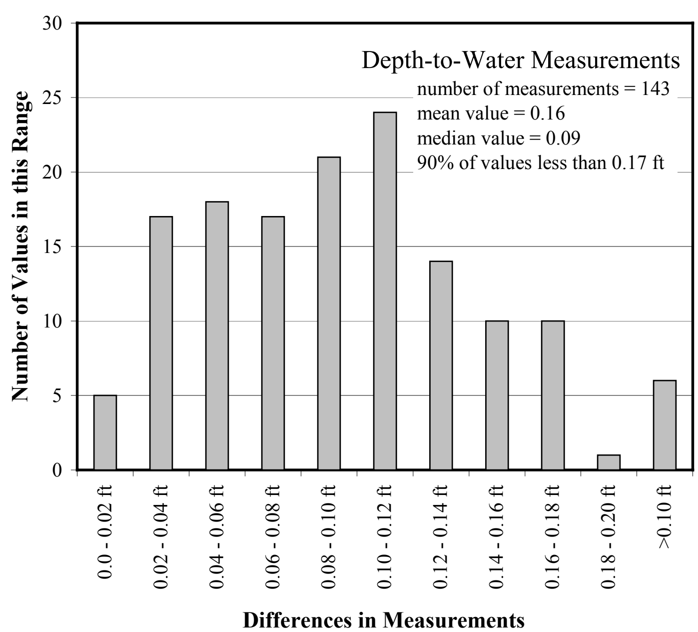


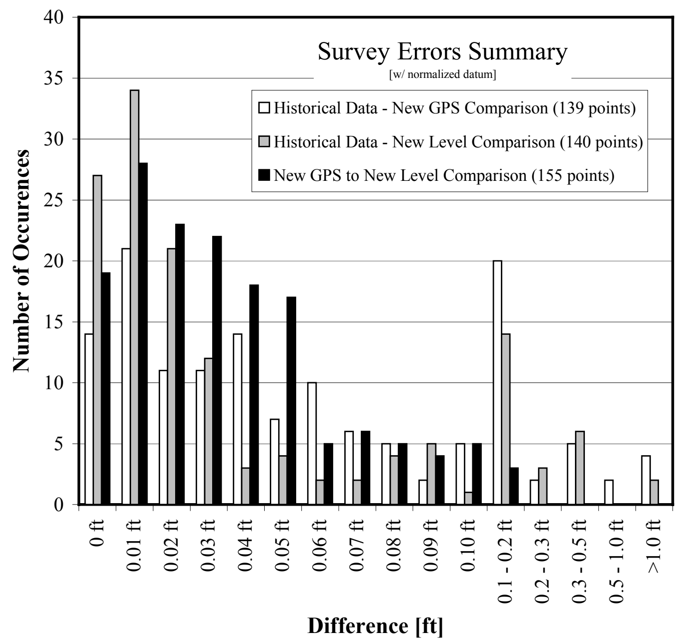
Figure 6.2 presents the differences in measurements between two different depth-to-water level measurement devices. This assessment was performed because water level measurements might be performed using a collection of measurement devices. Differences in measured depths-to-water between the two devices (Figure 6.2) were typically larger than the differences between individuals (Figure 6.1). The average difference between the devices was 0.16 ft, and 90% of the difference values were less than 0.17 ft.

6.2 ASSESSMENT OF TOP-OF-CASING ELEVATION SURVEY ERRORS

Currently, the use of geographic positioning systems (GPS) is standard practice in the survey industry. This technique is likely used by surveyors unless the specifications requested dictate the use of another technology. Survey techniques currently available include GPS-Static, GPS-Real Time Kinematic (GPS-RTK), and the standard level. Currently, the standard level and GPS-RTK reflect the range of precision available in the survey industry: The standard level with the greatest vertical precision is precise to 0.01 feet, while GPS-RTK is precise to 0.03 ft (per manufacturer specifications).

Since flow direction is far more sensitive to errors in vertical measurement, the goal of the study was to determine what error in vertical readings might be anticipated from standard measuring point surveys. Utilizing both GPS-RTK and standard level techniques, 17 facilities encompassing 175 monitoring wells were surveyed. GPS-RTK was utilized to provide northings (x), eastings (y), and elevations (z), while the standard level was utilized for elevations only. Analysis of the results for the two survey methods utilized showed a mean discrepancy between the GPS-RTK and standard level elevations of 0.03-feet. While not an actual measure of error, this discrepancy could be translated as potential error in the vertical measurement. Additional statistics for the study include a range of 0.21-feet and a standard deviation of 0.03. Based on the assumption that the standard level was considered the more accurate of the readings, it was noted that the GPS-RTK had a tendency to provide an aberrant reading at times. The frequency of discrepancies greater than 0.10-feet was 1-in 30, and greater than 0.05-feet was 1-in-5.5.

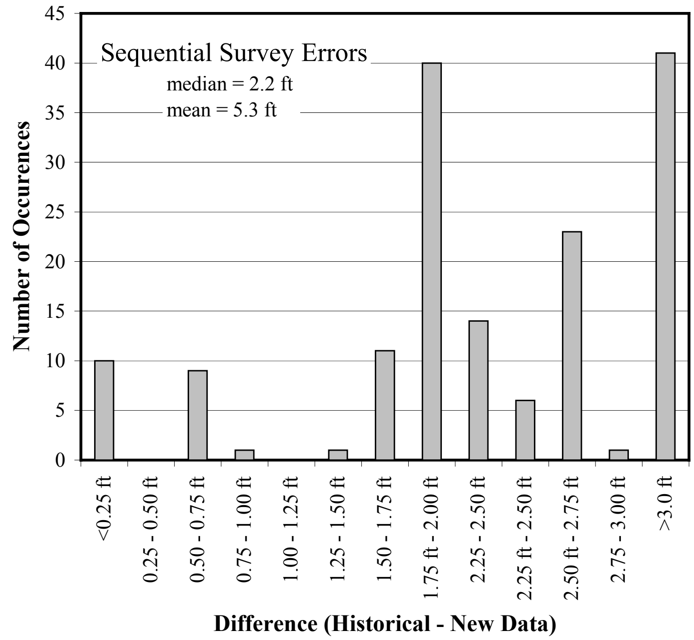
Figure 6.3.
Top-of-Casing Elevation Survey Error Assessment Results for Data Sets Re-referenced to a Common Survey Point.



Two comparisons between the new survey data and historical survey data were performed. In the first, elevations were referenced to a single well on site (using the elevation for that well for each data set), and then differences between these corrected elevations were computed. Those results are shown in Figure 6.3. The average difference was 0.08 ft and the median value was 0.02 ft. The maximum deviation was 2.14 ft.

In the second analysis, no attempt was made to reference the survey data to a common surveyed location. Instead, absolute differences between historical and new survey data were computed for each well with available data. This comparison is relevant because it is not unusual for sequential partial surveys (selected wells) to be conducted at LUST sites and then followed by compilation of all survey data. The results of that analysis are presented in Figure 6.4. As can be seen, errors associated with non-commonly referenced surveys can be very significant (>1 ft).

Figure 6.4.
Top-of-Casing Elevation Survey Error Assessment Results for Data Sets not Re-referenced to a Common Survey Point.



6.3 SIGNIFICANCE OF ERRORS RELATIVE TO FLOW DIRECTION DETERMINATION

It is beyond the scope of this study to conduct a detailed analysis of the flow direction errors caused by the types of elevation measurement errors discussed above (as this will depend on the specific number and placement of wells). However, it can be reasonably argued (as was done above), that a cumulative error of approximately 0.1 ft and greater is likely to cause a significant error in flow direction determination.

Based on the information provided above, it can be argued that the following conditions have the potential to cause a significant error in flow direction determinations:

a) Successive partial surveys of wells over time followed by compilation of the data into a single data set (cumulative groundwater elevation errors >1 ft),

b) Use of different water-level sensor devices during a single round of measurements (cumulative groundwater elevation errors >0.1 ft)

In addition, errors of roughly 0.02 – 0.05 ft should be expected from the combination of survey and measurement errors, even under the best circumstances. These errors should be considered in assessing groundwater flow direction at LUST sites.

7.0 SUPPLEMENTAL AQUIFER CHARACTERIZATION TESTS

Aquifer characterization tests (slug tests) were performed in a total of 32 wells from 11 sites determined to be representative of the state-wide range of geologic conditions. This was done because few aquifer characterization test results were available in the ADEQ LUST files (quantitative aquifer characterization is not required for LUST sites in Arizona).

Table 7.1. Summary of Aquifer Characterization Test Results.

Saturated Zone Geology	ADEQ Facility #	Number of Wells Tested	Hydraulic Conductivity[1] (ft/day)		
Sands, Gravels	1439	3	MW3 - 15.8	MW4 - 45.7	MW5 - 7.44
	1942	2	MW4 - 51.9	MW5 - 6.56	
	1301[2]	1	MW9 - 13.6		
Silts, Clays	1301[2]	2	MW4 - 0.31	MW8 - 0.005	
	5083	3	MW1 - 0.32	MW2 - 0.32	MW3 - 0.23
Interbedded Sands, Silts, and Clays	1224	3	MW5 - 0.07[4]	MW7 - 1.94	MW20 - 4.35
	1254	3	KW7 - 0.99	KW12 - 3.66	KW14 - 3.68
Mixed Sands, Silts, and Clays	1329[3]	3	MW3 - 39.7	MW4 - 54.9	MW6 - 14.8
	5476	3	MW14 - 14.0	MW17 - 5.87	MW19 - 20.8
Sedimentary Bedrock (limestone)	9063	3	MW5 - 0.37	MW6 - 4.54	MW7 - 2.75
Sand, Silts, Clays Volcanic/Igneous Bedrock	2428	3	TDI24 - 0.01	TDI25 - 0.20	TDI26 - 6.55
	2580	3	MW2 - 5.51	MW3 - 0.06	MW4 - 4.45
Total	11	32			

1. Based on slug testing with Bouwer and Rice analysis and aquifer thickness equal to the saturated thickness within the screened interval
2. Two distinct saturated geologies confirmed with boring logs
3. Geology listed as mixed sands, silts, and clays to sands, and gravels
4. Well historically has had free- product

Slugs were designed to displace a minimum of 1-ft of water in the monitor well, and where reasonable, more than one slug was utilized to maximize displacement. Water level changes were monitored using a 15-psi Solinst Levelogger programmed to log either 0.5-second or 1-second intervals during the first 10 minutes of monitoring. Hydraulic conductivity was determined using both the Bouwer and Rice (Bouwer and Rice, 1976) and the Hvorslev (Freeze and Cherry, 1979) methods of analysis. The results for aquifer testing are shown in Table 7.1.

8.0 ASSESSMENT OF THE POTENTIAL FOR IMPACTS TO WATER SUPPLY WELLS IN ARIZONA FROM LUST SITES

Appendix D focuses on: a) the development and use of a simplistic approach to conservatively estimate the potential impact of one or more LUST sites on the water quality of a specific water supply well, and b) discussion of scenarios most likely to cause adverse impacts and the frequency at which they might occur. Readers will find:

- A basic methodology for evaluating the potential impact to a production well from a single LUST site.

- A refinement of this basic methodology for evaluating the potential impact to a production well from multiple LUST sites, using information about LUST site and production well relative positions, LUST site characteristics, hydrogeologic characteristics, and production well pumping rate.

- A discussion of LUST-production well scenarios most likely to result in adverse impacts and the frequency at which they might occur; this includes a comparison of the spatial distributions of municipal production wells and UST sites in Arizona, a characterization of municipal production well characteristics, and consideration of results from the LUST file review and supplemental data collection.

Based on the example problems presented in Appendix D, it was hypothesized that the following scenarios could result in adverse impacts to water supply wells:

a) A residential well located within 1000 ft directly down-gradient from a LUST site and minimal biodegradation of the contaminant(s) of concern.

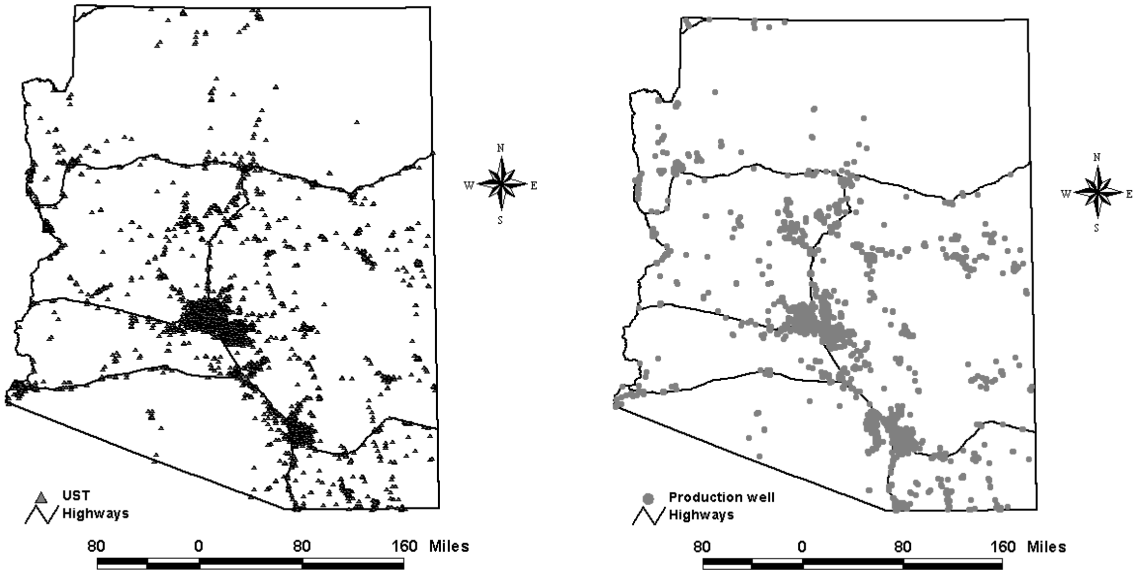
b) A municipal supply well in close proximity (i.e., 1000 ft) to at least 10 LUST sites within its capture zone and minimal biodegradation of the contaminant(s) of concern.

Thus, the relative positions of UST sites and water production wells in Arizona play an important role in the potential for impacts to water supply quality. There are approximately 9100 UST facilities in Arizona, each containing one or more underground storage tanks. Approximately 4600 (or about half) of the facilities are classified as having one or more LUSTs.

In the following, the spatial distribution of all UST sites is examined (rather than LUST sites), due to the possibility that the UST sites may have releases in the future, and the possibility that releases have occurred but have not yet been identified. This is a reasonable approach given the frequency at which releases occur from UST sites.

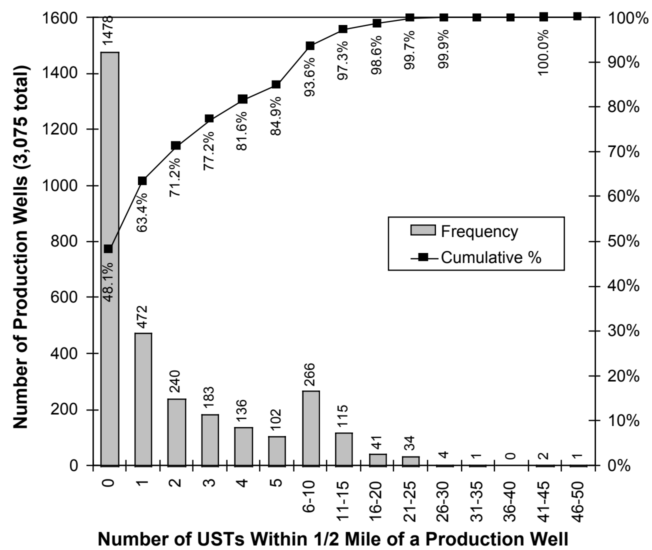
The August 2001 ADWR Well Registry Database lists over 146,000 wells. Well use types specified in the database include monitor, water production, cathodic, geotechnical, observation, abandoned, and several others. For the analyses summarized here, wells with use types specified as ‘water production’, and which were not specified as abandoned, were considered. Further, only wells with water use types of ‘utility (water co.)’ or ‘municipal’ were considered.

Figure 8.1. Spatial distribution of UST sites and production wells (municipal or utility) in Arizona.



Initially the spatial analysis was performed only for wells with water use types of ‘utility (water co.)’ or ‘municipal’. This filtering resulted in a set of 3075 production wells for which the spatial relationships to 9139 UST sites were examined. Figure 8.1 shows the state-wide spatial distributions of the municipal production wells and all UST sites in Arizona. The well data were obtained from the Arizona Department of Water Resources (ADWR) Arizona Well Registry Database in Geographic Information Systems (GIS) compatible format (August 2001). The UST data were obtained from ADEQ in GIS-compatible format.

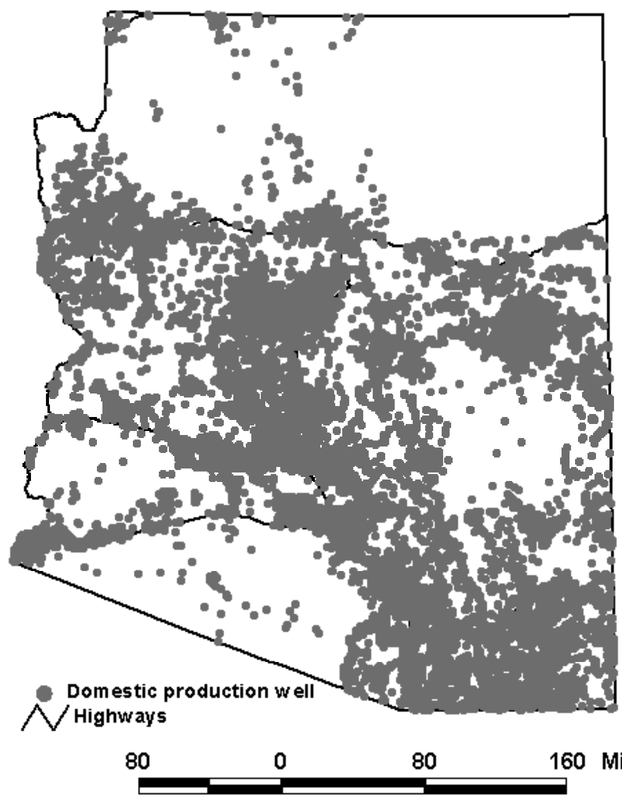
Figure 8.2. Histogram of Number of Production Wells Having the Specified Numbers of UST Sites Located Within One-Half Mile. The Total Number of Wells in this Analysis was 3075.



The relative positions of UST sites and production wells were characterized in two different ways. First, the number of UST sites within a one-half mile radius of each production well was determined, and the results for all sites are presented below in Figure 8.2 as a frequency plot. A radius of one-half mile was chosen for two reasons: a) the LUST file database and supplemental sample concentration vs. distance analysis suggest that dissolved concentrations typically attenuate significantly over distances less than one-half mile (although there are notable exceptions for MTBE plumes), and b) well locations are specified to within a ten-acre area (quarter-quarter-quarter section) in the ADWR database, and the point coordinates used in the database for any well are assigned the coordinates of the center of the ten-acre area; therefore, the use of distances less than one-half mile would have resulted in larger relative errors in the spatial calculations. The UST locations were determined by GPS and the error is on the order of a few feet. Therefore, assuming the errors in the UST locations to be negligible, the maximum error in the distance measurements between the production wells and the UST sites is about 470 ft (0.088 miles).

The results in Figure 8.2 suggest that nearly 50% of the production wells (1478 of 3075) are farther than one-half mile from the closest UST site. Those wells would be expected to have little or no risk of impact from typical LUST releases, although unusually large source zones, unusually long contaminant plumes, plumes from undiscovered LUST sites, or petroleum releases from other sources (e.g., surface spills) could impact the wells. Approximately 10% of the production wells are located within one-half mile of more than 10 UST sites, and 99% of the production wells have 25 or fewer UST sites within one-half mile.

Figure 8.3. State-wide Distribution of Domestic Water Supply Wells.



Though contamination of municipal-scale production wells has the potential to impact large populations, the number of these types of wells is relatively small when compared to the number of domestic production wells in Arizona (n>70,000). Figure 8.3 displays the state-wide distribution of these wells.

Determining the number of USTs within 1/2 mile (or any other distance) of all domestic wells was beyond the scope of this study. However, this analysis was conducted for Maricopa and Yavapai counties as these have the highest UST density and highest domestic well density, respectively. The results are presented below in Figures 8.4 and 8.5.

Figure 8.4. Histogram of Number of USTs Within 1/2 mile of Domestic Wells in Maricopa County.

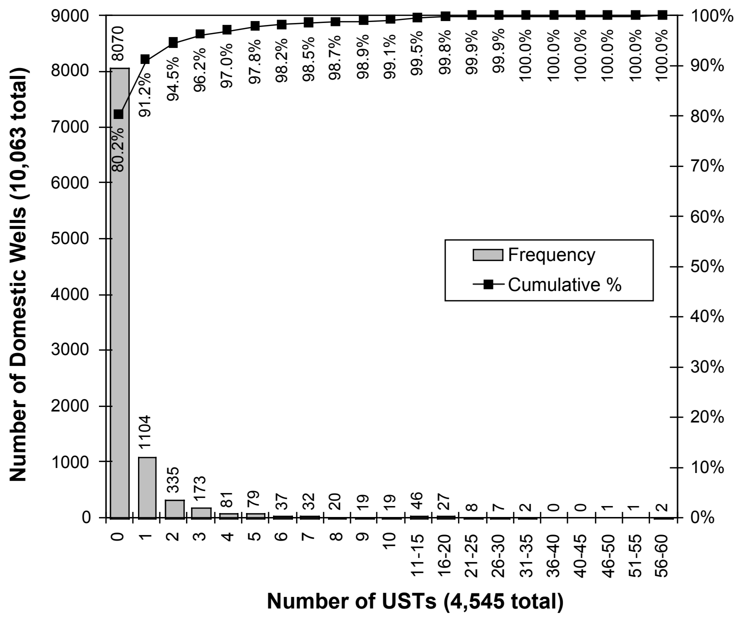
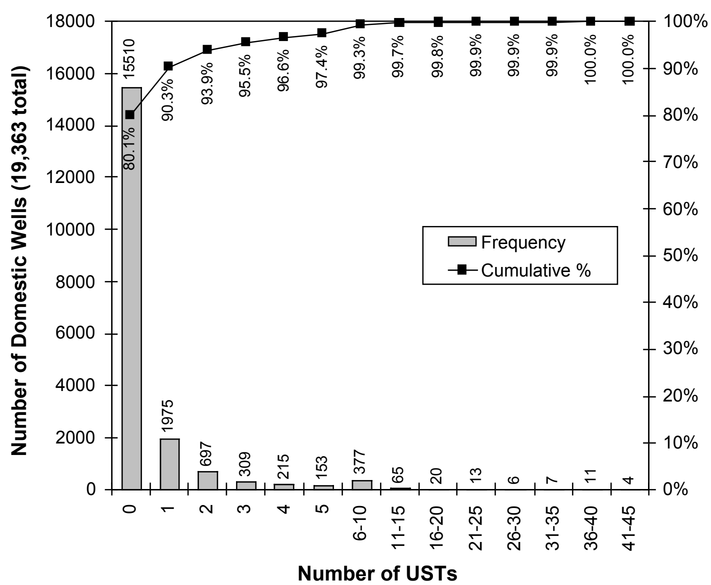


Figure 8.5. Histogram of Number of USTs Within 1/2 mile of Domestic Wells in Yavapai County.



9.0 REMEDIATION ANALYSIS

One of the objectives of this study was to assess the performance of in-situ remedial techniques in various Arizona LUST settings. Based on the LUST file review, remedial techniques used to date in Arizona include the following:

- Excavation (EXC)
- Air sparging (AS)
- Soil vapor extraction (SVE)
- Pump and treat (PT)
- Bio-remediation (BIO)
- Free-product removal (FPR)
- Oxygen releasing compounds (ORC)
- Natural attenuation (NA)
- Bio-venting (BIO V)

Initially, the ADEQ USTrack database was used to identify the number of sites with remediation activities and the technologies used at those sites. Table 9.1 summarizes the results, including the number of LUST closures associated with a particular remediation technology. Note that individual UST facilities can have multiple LUST listings: There are 4,567 facilities in Arizona with LUSTs, there are 9,198 LUST listings, and there are >9000 UST facilities in Arizona. *As such, the Number of Facilities With Closed LUSTs does not imply that the facility is closed, it only means that one or more of the LUSTs associated with that facility might be closed.* In addition, an individual site cleanup may involve the use of more than one remedial technology. As a result, the sum of all occurrences in a category can be greater than the total number of facilities at which remediation occurred.

Table 9.1. USTrack-Based Remediation Statistics.

Medium	Remediation Technology	Number of Facilities	# Facilities with Closed LUSTs	# Facilities with GW Priority Listing
Groundwater	In-situ air sparging	29	14	
	Free product removal	34	11	
	Natural attenuation	25	19	
	In-situ bioremediation	6	4	
	Pump and treat	11	5	
	None	1956	1772	
	Other	3	1	
	Unknown	1	1	
	Blank – no information provided	3100	2186	
Soil	In-situ SVE	127	104	48
	In-situ bioremediation	12	10	4
	Natural attenuation	32	28	8
	All ex-situ techniques (thermal, bio-remediation, asphalt blending, landfarming, aeration, etc.)	1106	1011	96
	None	968	870	64
	Other	33	30	5
	Unknown	2	0	1
	Blank– no information provided	3061	2127	696

Of the ADEQ LUST file review sites, 159 sites had, or were listed in the USTrack database as having, some form of remediation. Table 9.2 summarizes the findings with respect to frequency of technology application.

For the purpose of assessing technology performance, a minimum of one year of both pre-remediation and post-remediation data was desired. This requirement was used because it is known that many remedial technologies can effect apparent reductions in contaminant concentration in the short-term (weeks – months), and that these are not always sustained in the long-term if the system is prematurely terminated or not optimized.

In brief, it was discovered that use of these criteria eliminated most of the remediation sites from consideration, and as a result the data were insufficient to draw defensible conclusions concerning the performance or cost-effectiveness of remediation technologies at Arizona LUST sites. This is in part a reflection of the ADEQ data requirements (because closure can be granted based on only two monitoring events), and is also in part a reflection of the history of LUST activities in Arizona (to date, much effort has been devoted to the initial characterization of LUST sites, and less to remediation).

Table 9.2. Remedial Technology Use at Sites Identified by USTrack and/or the Study as Having Remediation and a Comparison of USTrack and Study Findings.

Criteria	Remedial Technology[1]											Single Technology Use	Multiple Technology Use
	None	AS	SVE	AS/SVE[2] Combination	FPR	EXC	NA	PT	ORC	BIO	BIO Vent		
Number of Sites Where the Study Identified Use of This Technology	10	33	83	31	45	34	11	12	11	2	4	88	61
Number of Sites Where the Study Found This Technology was Being Used Alone	---	1	31	18	24	22	6	1	1	0	2		
Number of Sites USTrack Had Identified Use of This Technology	82	19	29	14	10	18	22	7	0	4	0	37	31
Number of Sites Where USTrack Report of Technology Use Corresponded With Study Findings	---	8	24	4	5	6	5	5	0	0	0	30	10

1. AS=in situ air sparging, SVE=in situ soil vapor extraction; FPR=free-product recovery; EXC=excavation; NA=natural attenuation; PT=groundwater extraction and above-ground treatment (pump and treat); ORC=oxygen release compounds; BIO=bioremediation; BIOVent=bioventing
2. Not counted as a single technology

Sites were eliminated from consideration for a number of reasons; a summary of these is provided in Table 9.3.

Table 9.3. Reasons for Eliminating Files from Remediation Technology Analysis.

Technology	Problems Hindering Analysis	Total # of Sites	# of Sites Used in Conjunction With Other Technology
Natural Attenuation (NA)	Little active- and no post- remediation data	13	7
	Diesel site – Low BTEX concentrations		
	BTEX concentrations still high – No apparent response		
	Site closed based on samples collected during in situ air sparging		
	Other technologies used in conjunction with or prior to NA		
	Wells submerged – groundwater quality not known		
	ORC utilized – Unknown response from NA		
	Concentration reductions related to falling groundwater level		
BioVenting and BioSparging	Active remediation data showed little change - No post-remediation data	5	3
	Diesel site – very low BTEX concentrations		
	Only 1 pre-remediation event and post-remediation data from different wells		
	No discernible change in groundwater quality - Concentrations too low		
Pump & Treat	No discernible response	8	7
	Only 1 pre-remediation event and post-remediation data from different wells		
	Used in conjunction with or followed by other technologies		
	Some attenuation noted but remediation stopped		
	Free-product appears in numerous wells during/after treatment		
Oxygen Releasing Compounds (ORC)	No distinct change in wells with consistently detectable concentrations and sampling of well with highest concentration was discontinued	12	12
	Improper screened interval and no clear remedial response		
	Unknown start date – Possible use in conjunction with AS/SVE		
	Only 1 pre-remediation event and post-remediation data from different wells		
	Unknown stop date – Possible sampling at same time of treatment		
	Diesel site – Low BTEX concentrations		
	Some attenuation noted but samples were collected during treatment		
	No discernible change in groundwater quality		
Free Product Removal	Used in conjunction with or followed by other remedial technologies	46	23
	Sampling locations for pre- and post-remediation data differ		
	Diesel site – BTEX concentrations too low		
	Free product still present		
	No discernible change in groundwater quality		
	No water sampling performed to date		
	No monitor wells for the site		
	Concentration reduction likely related to the falling water table		
Soil Vapor Extraction and Air Sparging	Believe treatment still ongoing. Concentrations increase in some wells while decrease in others	27	15
	In progress – BTEX concentrations still high		
	Concentration reduction correlates with falling water table		
	Free-product still present		
	Concentration changes correlated with falling water table and rebound in concentration observed		
	Remediation in progress. Little to no active remediation data and no post remediation data		
	Remediation in progress - No discernible response		
	Sampling in well with high conc. was discontinued. Questionable response to SVE in another		
	Free-product appeared after treatment		
	No discernible change in groundwater quality - Concentrations too low		
USTrack Says Natural Attenuation	No groundwater quality data	8	0
	No groundwater monitoring wells – Site with soils data only		
	Concentrations low and several wells went dry		
	Groundwater conc. reductions correlate with drop in groundwater level		
	No discernible change in groundwater quality - Concentrations too low		
Air Sparging	No active/post-remediation data in the well with highest concentrations	14	13

Table 9.3 - continued. Reasons for Eliminating Files from Remediation Technology Analysis.

Technology	Problems Hindering Analysis	Total # of Sites	# of Sites Used in Conjunction With Other Technology
Soil Vapor Extraction	No discernible change in groundwater quality	52	22
	Remediation in progress – BTEX concentrations still very high		
	Remediation in progress – No discernible response		
	Pre-remediation wells are different from post-remediation wells		
	Little active/post-remediation data and concentrations are low and/or variable		
	Improper screened interval and no clear remedial response		
	No groundwater monitoring wells – Sites with soil data only		
	Concentration reduction may be correlated with falling water table		
	SVE cut short due to rising water levels – BTEX concentrations high		
	Concentration reduction prior to implementation of SVE		
	Free-product still present		
	Groundwater monitoring wells went dry and had low concentrations		
	Site still has high BTEX concentrations		
	Remediation in progress		
	No groundwater monitoring well data – Hydropunch data only		
	Area wide investigation – no specific data		
	No pre-remediation data and no discernible response		
	No pre-remediation data and post-remediation data collected 8 years after remediation ended		
	No pre-remediation data and little other data available		
	No pre-remediation data and concentrations were low to begin with Possible rebound in WQ concentrations		
	Sampling locations with pre-remediation data differ from those with post-remediation data. Source zone still had high BTEX concentrations		
	Little active/post remediation data. Improvements in WQ noted prior to SVE initiated		
	No post remediation data		
	Active and post-remediation data collected from submerged wells		
Excavation	Minimal data - No discernible change in groundwater quality– Concentrations too low	36	12
	Used in conjunction with or followed by other technologies		
	No groundwater monitoring wells – Site with soils data only		
	Free-product still present		
	No groundwater concentration data for excavation time frame		
	Groundwater monitoring wells went dry – no usable data		
	BTEX concentration still high – EXC followed by FPR and SVE		
	No apparent response following EXC and GW data very limited		
	No discernible change in groundwater quality - High BTEX concentrations still present and/or groundwater concentrations too variable		
	No discernible change in groundwater quality – Concentrations too low		
	Diesel site – BTEX concentrations too low		
	Sampling locations with pre-remediation data differ from those with post-remediation data		
	Only well with detects was destroyed during excavation and location was never sampled again		
	No groundwater quality data for several years following excavation and concentrations were too low to discern a response		
	Groundwater concentration reduction at site covers 10 year period following excavation and was difficult to relate specifically to excavation		